A Survey-driven Feature Model for Software Traceability Approaches

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Abstract. Traceability is the capability to represent, understand and analyze the relationships between software artefacts. Traceability is at the core of many software engineering activities. This is a blessing in disguise as traceability research is scattered among various research subfields, which impairs a global view and integration of the different innovations around the recording, identification, evaluation and management of traces. This also limits the adoption of traceability solutions in industry.

In this sense, the goal of this paper is to present a characterization of the traceability mechanism as a feature model depicting the shared and variable elements in any traceability proposal. The features in the model are derived from a survey of papers related to traceability published in the literature. We believe this feature model is useful to assess and compare different proposals and provide a common terminology and background. Beyond the feature model, the survey we conducted also help us to identify a number of challenges to be solved in order to move traceability forward, especially in a context where, due to the increasing importance of AI techniques in Software Engineering, traces are more important than ever in order to be able to reproduce and explain AI decisions.

1 Introduction

The need for traceability has always been salient in software and systems development. Across the years, there has been a continuous interest in developing techniques to facilitate the representation and analysis of traces and links between related artefacts. It helps explaining their execution and evolution as required in many software engineering activities and disciplines such as code-generation, program understanding, software maintenance, and debugging.

The importance of traceability was first recognized in system engineering, especially related to the development and certification of critical systems where it is a primary concern. As an example, traceability is part of any certification mechanism in all commercial software-based aerospace systems as stated in documents like the RTCA DO-178C (2012) [76, 62]. The consideration of various levels of abstraction in software development and the meaning of verification in model-based development paradigm –

which figures abstract representations (models) as the core artefact for conceptualization – was later introduced with companion documents (specifically, DO-331). The automotive industry has followed the same path with the construction of an international standard for functional safety, the ISO-26262 [45].

Despite these important evidences on the need for explicit (and automated) tracing abilities in software development, traceability is not widely adopted, even less automated. There is little feedback from its concrete use in industry beyond the critical domains above [75] and when existing, it ends up being mostly a manual process [56]. Moreover, with no standard definition or representation of traces, it is difficult to bridge the gaps between the different partial traceability solutions existing in research subfields [5, 102, 101]. Even the software engineering body of knowledge does not seem to properly consider the power of traceability as it only *mentions* traceability once [16].

The foundation for an effective modelling of traceability is disseminated among a profuse literature. Approaches vary greatly in their means and goals. Moreover, most focus on specific pairs of artefacts and therefore remain difficult to integrate in different industrial scenarios. Note also that this happens in a context where artificial intelligence techniques are being integrated in development processes, raising the need for more powerful reproducibility and explainability concerns, both requiring the assistance of traceability mechanisms.

This paper aims to provide a comprehensive perspective on the state of the art of traceability techniques in software development and their limitations. With the short-term goal of facilitating the evaluation and comparison of current solutions. And the mid-term goal of accelerating the development of new traceability solutions that could benefit from the existing ones thanks to our new conceptualization in the form of a feature model describing the potential dimensions and concerns a traceability solution may wish to consider. We do not create the feature model only based on our (partial) knowledge and expertise in the domain. Instead, we ground our classification with a survey of the published literature in this field. According to this survey, we group the traceability features in three main dimensions: trace definition, trace identification and trace management, with the corresponding feature hierarchies for each of them.

The paper is organized as follows. After a brief introduction, we discuss in Section 2 an overview of the scientific work related to traceability. We then remind some basic terminology in Section 3. Section 4 describes how we conducted our literature review and Section 5 presents a detailed feature model derived from the survey of the retrieved works. This analysis also helps us to propose a number of discussion points and open challenges in Section 6 before concluding this work.

2 State of the art of software traceability

Traceability was proposed, from the very beginning of software engineering, to ensure that a system being developed actually reflects its design. Already in the original NATO working conference, quality projects were praised for making "the system that they are designing contain explicit *traces* of the design process" [81]. From that point on, traceability has been studied from a myriad of perspectives, dimensions and applications.

Historically, traceability historically started in requirement engineering. The very idea to follow the impact of changes in the requirements to other artefacts (and backward) was then and remains today the most prominent goal [34]. Precise and rich requirements allow a proper follow up of their later implementations [21]. Through time, the advantages of using traces – *i.e.,* the record of (inter-)dependencies between artefacts, has revealed to be applicable to most if not all sphere of software maintenance. The use of traces spans from software certification and testing, feature location, debugging, code generation, and so on. With the proliferation of traceability purposes, some authors explicitly asked for better sharing of experiences in using traceability [35] and evaluating the solutions existing so far [91]. Surveys and literature reviews trying to group and compare them began to appear as well, though most of them focused on specific subareas such as requirement engineering [34, 15], model-driven development [31, 101, 70, 86, 63], software product lines [96, 4], benchmarking [91], and information retrieval [23, 13, 38]. To complement these scientific surveys, Konigs *et al.* survey industrial application of traceability approaches, showing its limited penetration [51]. Neumuller *et al.* show that the adoption is worse in small businesses where traceability is even less automated [67]. Finally, Charalampidou *et al.* add to the conclusion of other surveys that "although many studies include some empirical validation", there is still much to be done with respect to validation and reproducibility [20].

This is aggravated by the fact that, as pointed out above, many of the proposals belong to different research subfields, which limits the discovery and awareness of alternative solutions. For instance, authors point out that researchers in requirement engineering and in model-based development do not communicate enough among each others [101, 70, 85]. This lack of communication and shared understanding is one of the open challenges in the traceability domain [22, 5, 28]. To solve this issue, several works aim at proposing specific traceability models. Unfortunately, many investigations suffer a lack of generalizability due the specific nature of the problem being solved (*e.g.,* certification conformity [50], model transformation coevolution [37]), or the specific nature of the solution considered (*e.g.,* w.r.t. its language: SysML [65], w.r.t. its engineering field: SPL [4], agile [60]).

As an example, the automatic identification of trace links is one of the most studied features. There are plenty of proposals but as they are evaluated using different datasets and configurations, they cannot be directly compared [89, 38, 13]. Another example would be model-driven engineering, where the use of traceability specific languages together with automated model transformation appears as an ideal soil to grow end-to-end traceability. This led authors to present classifications and terminologies for a systematic perspective on the tracing of MDE development [70, 28, 85]. Nevertheless, proposals tend to focus on a specific model-driven engineering problem: the co-evolution of models and transformations [3] instead of aiming for more general solutions. Mustafa *et al.* argue that "the main issues in traceability nowadays are building traceability models that can accommodate the capturing of traceability information and providing common semantics for trace links" [63]. As a result of this confusing situation, authors asked for more standardized practices. Two proposals gather terminology for fundamental and model based terminology [35, 44]. We take our general knowledge

about traceability from them and add to their definitions an actionable categorization for existing and coming traceability approaches.

We agree with these authors that this lack of *de juro / de facto* standard is hampering the benefits of current solutions and hindering evolution in the field. This paper intends to cover this gap by proposing a traceability characterization that stems from the analysis of existing proposals. We believe this model can be useful to researchers trying to improve traceability techniques in any subfield and to practitioners looking for a way to compare and choose the traceability solution that best suits their needs.

3 Towards a common traceablility terminology

A clear conclusion from the previous section is the lack of a common agreed upon conceptualization for traceability that helps evaluating, comparing and reusing traceability solutions over a variety of scenarios and application domains. Thus, the *incoherency problem* still arises in traceability research [100]. Even if an individual article makes a claim that withstood rigorous testing and statistical analysis, it might not use the same words as an adjacent article, or it would use the same words but intend different meanings. For instance, the term *traceability* is used to designate both the ability to trace system elements, and the traceability links (the relations) themselves [15, 5].

Therefore, before proposing our global traceability feature model to classify traceability solutions, we first recap the different usages of the key traceability concepts and propose a unified definition that we will use in the rest of the paper.

3.1 Traceability components

Traceability research refers mainly to a definition from Gotel *et al.* that defines traceability as the ability to describe and follow the life-cycle of a requirement, from its initial specification to the design and code elements of the system implementing it [34]. This is still the most popular meaning for traceability [15, 8] even if modeling approaches try to generalize this notion by seeing traceability as a valuable tool to link all types of linking artefacts at either the same or different levels of abstraction [55, 95].

Regardless of the specific interpretation of traceability, we observe a division of knowledge into four main areas:

- **Strategizing traceability**. It involves defining the explicit traceability purpose for the project at hand and how to best reach that goal. Maro *et al.* address the importance of a coherent strategy. The authors propose an introductory methodology to "provide support for establishing a traceability strategy that allows the organization to achieve its goals and measure the impact of [its] traceability strategy" [60].
- **Trace and artefact representation**. It covers the design / adaptation of a language to be used to define the traces and decisions regarding its syntax, expressiveness, variability, integration, etc. For instance, this can be done by means of creating a full traceability domain-specific language.
- **Trace link identification**. It designates the identification of traces in a software system, be it a post-requirement assisted elicitation, a live record during a system

execution or an automatic AI-based inference process. This latter approach is the motto right now to help the identification of links between heterogeneous artefacts.
– **Trace management**. It refers to the ways to use and maintain the traces. This includes tool support for the persistence, retrieval, and analysis of traces.

The first area is a high-level concern that influences the requirements of the other three to cover the specific needs of a project. These three will therefore be used to structure our feature model later on. Note that the representation component should be part of any traceability solution as it is the base component to be able to, at the very least, express traceability information.

3.2 Traceability glossary

We propose some general definitions for the most frequently encountered traceability terms while searching for and studying solutions for traceability in any of the above categories. These definitions, mostly borrowed from past literature [35, 44], aim to encompass the different uses and dimensions of traceability depicted above. Our set of terms is not exhaustive but provide a common core generic enough to be then adapted to specific scenarios. This is also why we try to be precise with the definitions, while also offering room for slightly different (but compatible) interpretations.

– **Traceability** is the ability to trace different artefacts of a system (of systems). Gotel *et al.* define traceability as "requirements traceability [which] refers to the ability to describe and follow the life of a requirement, in both a forwards and backwards direction" [34]. Gotel's definition has been extended to MDE software traceability as "any relationship that exists between artifacts involved in the software engineering life cycle" [2].
– A **trace** is a path from one artefact to another. A trace is composed of atomic **trace links** that directly relate artefacts to each others. The representation of traces, their data structure and behaviour, is defined in a traceability grammar or metamodel [25] depending on how the trace language is defined. In any case, the language definition specifies the concepts and relationships available to define traces. As discussed before, no standard language has emerged yet.
– An **artefact** can be any element of a system - *e.g.,* unstructured documentation, source code, design diagrams, test cases and suites... The nature of artefacts follows two main dimensions: the life cycle phase they belong to (*e.g.,* specification, design, implementation, test), and their type (*e.g.,* unstructured natural language, grammar-based code, model-based artefact). The **granularity of artefacts** is the level to which artefacts can be decomposed into sub parts. We call a **fragment**, the resulting product of the decomposition of an artefact. A fragment can be itself broken down into smaller parts (or sub-fragments), and so on.
– A **trace link** is a direct relationship between two artefacts. Links can be typed to better support the heterogeneous nature of traceability applications. The type of the link can help express the rationale behind the relationship - it informs not only *how* artefacts are linked but also *why* [56]. Typing is a primary concern in conceptual modeling in general [68]. This definition of a *link* is consistent with the concept of link in popular modeling languages like UML or SysML.

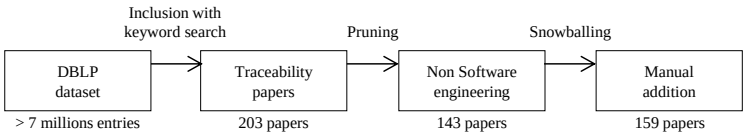

Fig. 1: Survey Process.

Links can be explicit or implicit. An **implicit link** shows artefacts bondage at a syntactic or semantic level without the need for an **explicit link** to be part of the model (*e.g.,* a binary class and its respective source code artefact are implicitly "linked" to each other, yet this bondage is not part of any language or grammar definition) [70].
– An **agent** is the (human) actor accountable for an artefact, or a link.
– **Trace integrity** is the degree of reliability that bares a trace. It is an indirect measure that includes, for example, both the age of a trace, the volatility of artefacts targeted by the trace, and the automation level of tracing features.

On top of these concepts, a recent work, by Holtmann *et al.*, makes a distinction between a *foundational* and a *specifically model-based* terminology [44]. This latter add a specification for *model* and *language* scope definitions, as well as a distinction between *relational* and *referential* trace links.

– **Intra/Inter model** trace links differentiate between relations that links elements of the same instance of the language and relations linking elements from distinct instances. This distinction was first introduced by Lindval *et al.* [54].
– **Intra/Inter DSL** differentiate between relations that links elements in models based on the same language and relations that links elements in models from different languages.
– The distinction between **Relational and Referential trace links** lies in the instantiation (or not) of the instance link. "A relational trace link is represented by *a dedicated node* with incident directed edges pointing to the trace artifact nodes" whereas "a referential trace link is *a directed edge* from one trace artifact node to another trace artifact node". In the latter case, a trace link is commonly represented as a *property* of the source artefact.

Some of these concepts will explicitly appear in our feature traceability model while others act as requirements and usages that should be supported/facilitated by the features in the model and taken into account when choosing a specific traceability solution depending on how well that solution covers the specific features of interest for the project at hand.

4 Traceability Survey method

In this section we depict the methodology we followed to collect papers proposing traceability solutions, including at the very least the core *representation* component (see previous section). The analysis of these papers will give rise to the feature model we will present next.

The selection process combined the manual selection of a few approaches based on our own experience working in this field and/or covered by other meta-studies [35, 5, 22, 38] together with a systematic literature search mining bibliographic data sources following the literature review process established by Kitchenham and Charters [48]. Fig. 1 depicts the three main steps of the process.

4.1 Data source and search strategy

We used DBLP [1] as our core electronic database to search for primary studies on traceability. To avoid missing possibly relevant approaches, we decided not to put a specific period constraint for the search, but we limited the scope of the search to papers of five pages or more to avoid opinion and vision papers, posters, tool demos and other types of short papers to reduce the number of results while maximizing their quality.

Based on the topic of this survey, we defined the terms of the search query according to the recommendations of Kitchenham and Charters [48]. We apply the query on the title and abstract of potential relevant publications. As using very generic terms like "trace" or "traceability" returned thousands of results, we decided to combine in the search query trace-related keywords with language-related ones since we target traceability proposals that, at the very least, discuss how traces need to be represented / expressed and not only discuss their application to some specific domain without going deep into the details. As many traceability languages are model-based, we included model, modeling, and other core MDE concepts as part of the language variations. This resulted in a total of 203 papers.

Here is the exact query we applied:

```
.*(([Tt]rac(eability|ing))|([Tt]race[rs])).* AND
.*(([Mm]odel[- ])(([Dd]riven)|([Bb]ased))|
MD[DAE]|Model[l]ing|[Tt]ransformation| DSL|[Ll]anguage).*
```

4.2 Pruning

In what follows, we describe our inclusion and exclusion criteria. We further explain how we applied these criteria on the previous set of papers.

Inclusion criteria	Exclusion criteria
1. the paper is a technical contribution	
2. the paper is about tracing in software engineering	1. the paper is not a primary study
3. traceability is the main concern of the paper	

Before we applied these criteria on the potential papers fetched by our query, we removed automatically papers of less than 5 pages long. We also automatically extracted papers whose titles mentioned "biology", "education", "kinetics", "logistics", "physiology", "physics", "neuroscience", "agriculture", and "food" which appeared each in a couple of results. We manually examined the 183 papers left and excluded 40 papers that did not fulfill the criteria or were duplicates.

4.3 Snowballing

At the end of the previous steps, we double-checked that we did not miss any potentially relevant approach due to a number of reasons, *e.g.*, some workshop papers are only indexed by ACM or papers that may be using different synonyms for traceability like "composition" or "extension".

Finally, we added papers we were aware of based on direct knowledge or from other surveys we had read (if not already in the result set) and a few more we found by snowballing on the selected papers references. They amount to a total of 10 more papers. This lead to a final result of 159 papers. Among them, there are 41 journal articles, 82 in conference proceedings, and 36 workshop reports (see Table 1). Fig. 2 shows the chronological distribution of the selected publications.

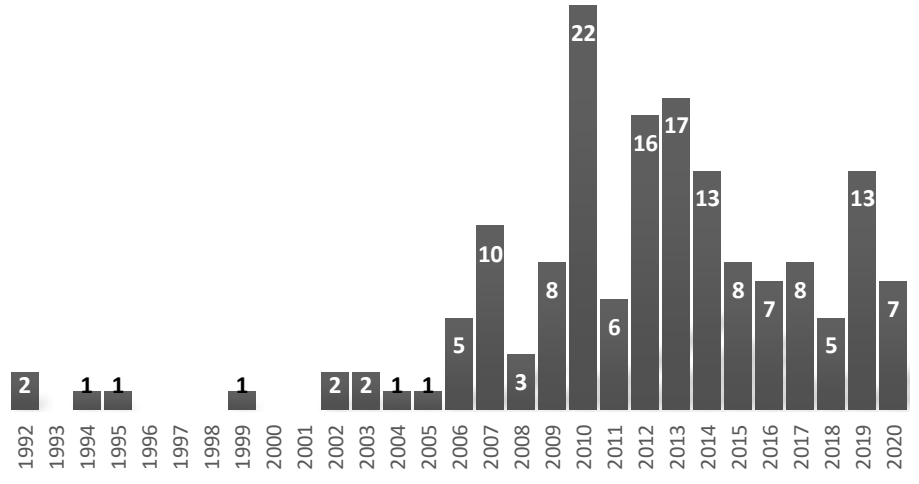

Fig. 2: Papers selected related to traceability and modeling.

Publication type	
Journal	41
Conference	82
Workshop	36

Table 1: Publication types of the selected papers.

4.4 Threats to validity in the selection process

We acknowledge limitations in the execution of our survey method. First, we only used DBLP as a source database. Yet, it is recognized as a representative electronic database for scientific publications on software engineering and already contains more than five

million publications from over two million authors. Setting the limit based on the number of pages alone to elude short papers is another threat to validity. Yet, it is a reproducible practice that limits the number of papers to analyse and thus helps concentrate on the topic rather than the engineering of the survey. Then, the vocabulary related to traceability is scattered among various fields of application with their respective nuances. We mitigate the risk of missing papers by manually adding papers that were not using variations of this term but were still referenced by papers that did. Still, focusing on traceability as a key term was also a conscious decision as we wanted to characterize the works in this field, focusing on those papers that define themselves as part of it.

5 A feature model to characterize software traceability

This section presents our feature model describing the traceability features and dimensions found in the analysis of the literature. Our feature model groups them by similarity and provides additional descriptions on the most important aspects of each one, *e.g.*, different existing alternative implementation of the same feature and/or the most/the least studied ones in each group. Next subsections provide some background on feature modeling and then zoom in to each of the three main dimensions of traceability: trace representation, trace identification, and trace management.

5.1 Introduction to feature modelling

A feature model leverages features as the abstraction mechanism to reason about product variability. It is a hierarchically arranged set of features, where relationships between a parent feature and its child features may be categorized as: *and* – all subfeatures must be selected, *alternative* – only one subfeature can be selected, *inclusive or* – one or more can be selected, *mandatory*, and *optional* [47]. Each feature represents an increment in product functionality.

Feature modeling is a technique that has been intensively used for documenting the points of variability in a software product line, how the points of variability constraint one another, and what constitutes a complete configuration of the system. But beyond product lines, feature models are also more and more used to shed light on complex domains by representing the core concerns and variation points in a complex ecosystems (*e.g.*, [17]), as we do in this paper.

5.2 Trace definition and representation

All approaches must discuss their representation of trace artefacts even if they can differ on the type of traces they consider and the application they target. Representations are so diverse that our survey selected more than 80 papers mentioning their own distinct definition for traceability – with 20 metamodels effectively depicted in those papers. Some researchers present generic graph-based representations [87, 36] while others focus on representations much more specific to a concrete application like a metamodel for change impact analysis [33] or multi-model consistency [94]. In both cases, what traceability approaches target and how they represent a trace is differently approached.

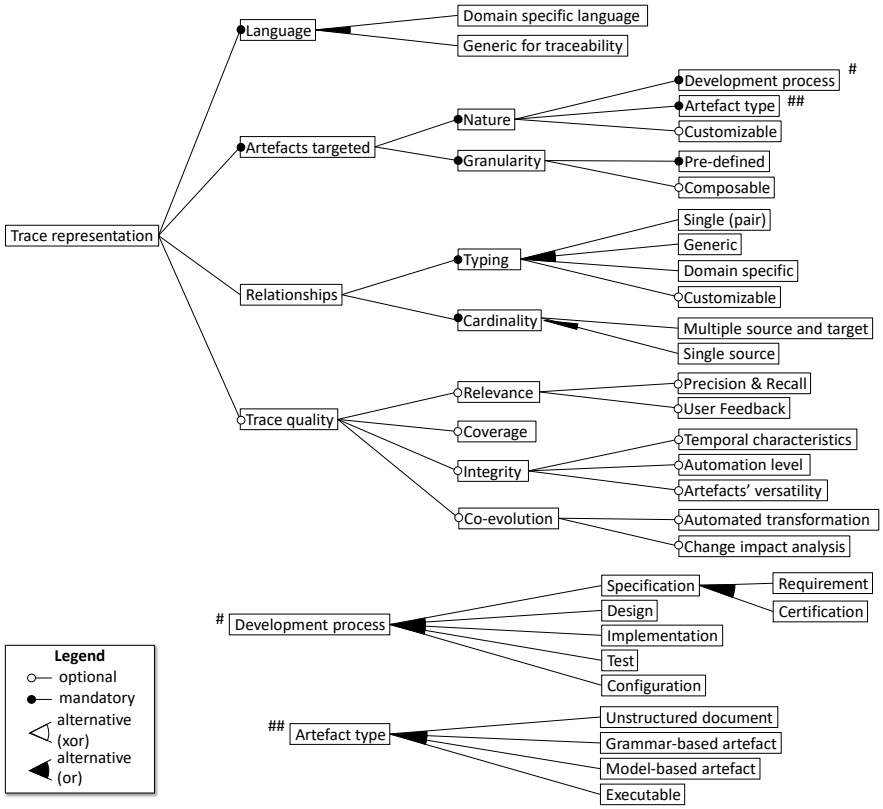

Fig. 3: Features related to the representation of a trace.

Fig. 3 shows the hierarchy of features related to the definition and the representation of trace artefacts. A peculiar focus is put on the typing of traces' relationships. Typing relationships is important to add semantics to the trace so that the engineer can know not only what the linked artefacts are but also why they are linked. As such, it facilitates the application of traceability solutions to specific domains. We also detail the genericity of the language, the nature of the artefacts covered by the traceability proposal, and the possibility to annotate traces with quality properties.

We would like to remark the contribution of model-based approaches for traceability in this section. The use of MDE tooling such as ATL [84, 46], or the Eclipse Modeling Framework (EMF) allows the automated generation of traceability information as a side effect of executing operations [31, 101]. The modeling community has proposed metamodels for end-to-end traceability [42, 40], as well as metamodels specific to engineering domains such as model transformation [46, 4, 97, 11] or software product line [46, 97]. Paige *et al.* call for more flexible modeling where models of different formats are associated to each others' with annotations that allow automated bond or dependency inference between both application and engineering domains [89, 72].

Language Languages specific to traceability provide the ability to represent trace artefacts with increased relevance and accuracy. Yet, they often suffer the limitation to be built *ad hoc* and lack a significant power of reusability into other domains. Among these domain-specific languages for traceability, some authors attempt a generic definition of traceability [42, 7] while others provide a language specific to a single domain, *e.g.*, traceability for software product lines [4].

We found few studies interested in the use of general-purpose software language for traceability - even though this would be appealing to industrial partners interested in instrumenting their legacy systems code with traceability information to facilitate future evolution or migrations [65]. Representing traces in spreadsheets, text files, or databases, shows better learning curves than using a domain specific language, but at the cost of a cognitive gap between software engineers and domain experts. As an unfortunate consequence, "the maintenance costs turns out to grow accordingly [to the usability of generic representations] and team members fail to keep the trace artefacts up-to-date" [21].

A potential sweet spot lies in the making of orthogonal approaches that “plug” traceability concerns on top of other languages to benefit from an existing language structure while keeping most of the benefits of using a DSL.

Artefacts targeted We distinguish between the nature of the artefacts targeted by traceability purposes and their granularity as both dimensions are important. For the nature aspect, on the one hand, investigations differ on the development phase they target. Linking requirement specifications to design and code level predominate in the literature with more than 50% of the papers in the survey addressing requirement traceability. Other phases such as test and verification are targeted as well but in a lesser proportion (10 approaches). On the other hand, the type of the artefacts is important to deduce the level of potential generalization to other phases of the software lifecycle. Papers focus on four different types: unstructured document, structured as grammar-, and model-based artefacts, and binaries.

With regard to the granularity of the artefacts targeted, *i.e.*, their level of decomposition, few approaches go for a customizable granularity to adapt to artefact hierarchies [42, 60] while most of the others focus on specific types of artefacts (*e.g.,* to concentrate their work on specific optimizations of trace identification).

Relationship types As many authors have demonstrated, offering to the user the ability to define personalized types of relations between the artefacts of a system fosters the comprehensibility of the traces produced [68]. We distinguish between approaches offering predefined types and approaches allowing custom typing. Often the predefined types relate to the field of software engineering (implements, inherits, uses, executes ...), but not only. For example, Maletic *et al.* mention that a separation between *causal*, *non causal*, and *navigation* relationships can be appropriate [57]. Predefined types allow increased monitoring and user-friendliness to developers. They are found in most contributions relating the optimization of trace identification. On the other hand, allowing users to define the types of relationships specific to their area of expertise helps to fill the gap between the design and the use of tracing functionalities [102].

Obviously a fixed typing facilitates the analysis of the traces as the potential set of semantics and interpretations are fixed while offering domain-specific types increases

the usability and comprehensibility of the approach. As an example, SysMLv2 is offering a more powerful mechanism to define links between artefacts compared to the previous SysML version (where we had a sole dependency-like mechanism).

The literature shows also a distinction between approaches considering relationships with multiple sources and targets and relationships allowing only a single source.

Trace quality In most of the papers, quality aspects are barely mentioned. It seems quality of the generated traces is not a major focus, or at least storing and annotating the traces with such information is not. Yet, a few studies mention coverage and integrity. The coverage of a set of execution traces is used in approaches for software testing [32]. Coverage is also used by Rath *et al.* who address the problem of missing links between commits and issues with a classifier they train on textual commit information to identify missing links between issues and commits (*i.e.,* a lack in the coverage indicates such missing links) [82]. Matrix-based visualizations are particularly fit to assist coverage related tasks (See Section 5.4). Integrity of traces is addressed in work on model transformation where co-evolution figures an automatic verification of their coherence with other (versatile) software artefacts [94, 92]. In the same manner, Heisig *et al.* tag links which ends artefacts have been modified or deleted to inform the user of such changes [42]. The co-evolution of traces implies measuring distances between artefacts (syntactic, cognitive, geographic, cultural...) [10]. It also refers to the analysis of the changes of the system that impact traceability artefacts [33, 98]. In our survey, nine papers address artefacts co-evolution and 17 tackle model transformation limitations. These latter are a valuable tool to automate co-evolution tasks. In the many studies focusing on the optimization of link identification, the quality of the results is mainly evaluated with precision and recall measurements and never rely on inherent trace artefacts characteristics. Few researchers include a user feedback [13].

5.3 Trace identification

Fig. 4 shows the hierarchy of features related to the identification of traces with four main possible categories: the manual elicitation of traces, their live record during execution and evolution, rule-based alternatives to assist the user with automation potential, and AI-augmented identification with domain contextualization.

Manual elicitation Manual elicitation makes possible to create traces in an *ad hoc* manner. As an example, one of our industrial partner chose to hire a developer to elicit trace links necessary for a certification commitment. This was chosen rather than a (semi-)automated approach, as they were not convinced the effort of augmenting an existing tool would pay off for that specific project.

Recording instrumentation Teams can instrument the live record of traces during the execution and the evolution of software artefacts. This way traces recording the system changes are a side-effect of those same changes. There are initiatives to instrument existing languages such as ATL with rich log generation [84, 52], while others consider trace record an aspect that can be weaved with current existing languages [78, 84]. Ziegenhagen *et al.* mix execution traces with metadatas [104], and use developer interaction records [103] to enrich existing traceability artefact.

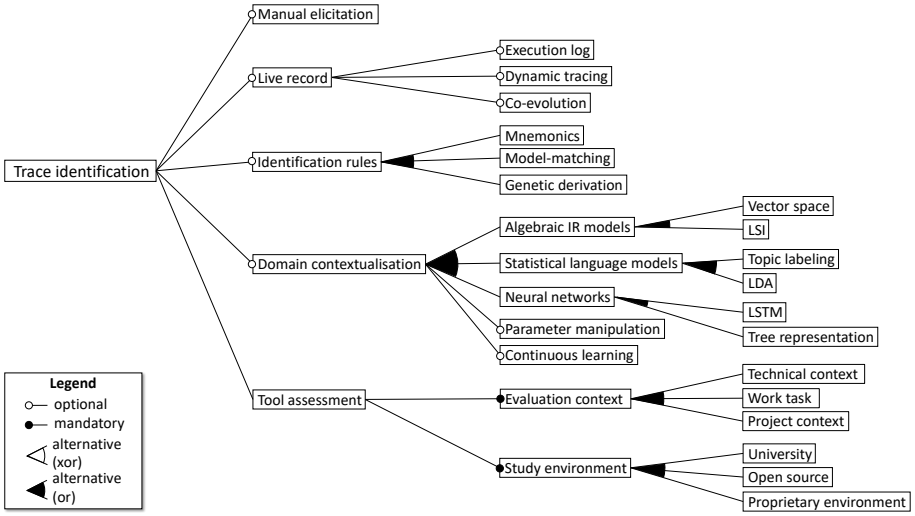

Fig. 4: Features related to the identification of trace links

Model transformations are considered the hearth and soul of software modeling and, consequently, numerous studies attempt to enrich trace generation during transformation execution [97, 83, 52]. This ubiquitous integration (see Fig. 5, bottom branch) allows a semantically rich tracing of target and source artefacts [71]. Unfortunately, this option can only be applied when the system is being built, not when the system is already in place.

Identification rules Once a system is in place, teams can identify rules that help retrieve and maintain traceability relations [64, 93]. Nentwich *et al.* describe a novel semantics for first-order logic that produces links instead of truth values and give an account of their content management strategy that provides rule-based link generation and consistency check [66]. At the model level, Grammel *et al.* use a graph-based model matching technique to exploit metamodel matching techniques for the generation of trace links for arbitrary source and target models [36], and Saada *et al.* recover execution traces of model transformation using genetic algorithms [83].

Domain contextualization Back in 1992, Borillo *et al.* published an article on the use of information retrieval techniques for linguistics applied to spatial software engineering [14]. This precursor work opened the box for AI-augmented traceability where machine learning algorithms help extract knowledge specific to the application domain (later called domain-contextualized traceability [39]). This is specially useful when the source (or target) of the trace link is an unstructured document or when such document is key to infer traces among other artefacts.

Today, domain contextualization by means of machine learning for topic modeling, word embedding, and more generally knowledge extraction from unorganized text documents, is the most popular traceability feature [38, 102]. This collective effort made

the identification of bonds between requirement specifications and other artefacts possible with a gradually improving precision [6, 23]. Studies on domain contextualization are separated into three subgroups according to the type of tools used (algebraic information retrieval models, statistical language models, and neural networks). For example, Florez *et al.* derive fine-grained requirement to source code links [30], Rath *et al.* complete missing links between commits and issues [82], Marcus *et al.* identify links between documentation and source code [59]. An interesting publication from Poshyvanyk *et al.* shows that mixing expertise both in information retrieval techniques and engineering domains gives far better results than when taken separately [79]. McMillan *et al.* add that using structural information together with textual information benefits automated link recovery (between requirements and source code) [61]. In total, we found 22 approaches dedicated to this topic alone in our survey. We do not discuss in this paper the techniques related to data collection and training optimization. These are important features for automated learning which are discussed in depth in specialized literature.

Teams are also using genetic algorithms to cope with the variety of algorithms and parameters these approaches use [58, 73], and structural information to foster methodologies interweaving [74]. Unfortunately, a common critique rose against these positive results. Too many teams compete with each others to accomplish a better precision and recall when there is no standard to the effective quantification of tracing artefacts into such variables. Too few attempt at qualifying the overall relation between these measurement and the effective impact on software development [22].

In that regard, Shin *et al.* propose a set of guidelines for benchmarking automated traceability techniques. Their evaluation (of 24 approaches) shows that methods of evaluation (when they are used appropriately) sometimes are not suitable to other application domains and that the variation in results across project is not investigated [91]. This corroborate Borg *et al.* who, in a systematic literature mapping on information retrieval approaches to traceability, notice that there are no empirical evidence that any IR model outperforms another consistently [13]. The ability to continuously improve the learning process is mentioned in the literature but we found no evidence of its application.

Tool assessment Very few of the traceability approaches have been empirically assessed on industrial use cases. The actual trend to report solely for precision and recall values indicates an important issue in the automated identification of traces and may justify the weak investment of industry in this sector [13, 69].

Borg *et al.* published a taxonomy for information retrieval techniques applied to traceability [12]. They emphasize the importance of the assessment of the tooling used to derive or identify traces. More specifically, the authors draw a differentiation between two orthogonal dimensions: the evaluation context that precises *where* in the context the tool is assessed (*e.g.,* at a technical, work task, or project level); and, the study environment that shows the kind of data used to fulfil the assessment (*e.g.,* proprietary, open source, or academic). These features will affect the measurable attributes used for the assessment as well as their generalizability.

5.4 Trace management

Fig. 5 shows the hierarchy of features related to the management of trace artefacts: their maintenance, integrity, persistence, and integration in running software systems.

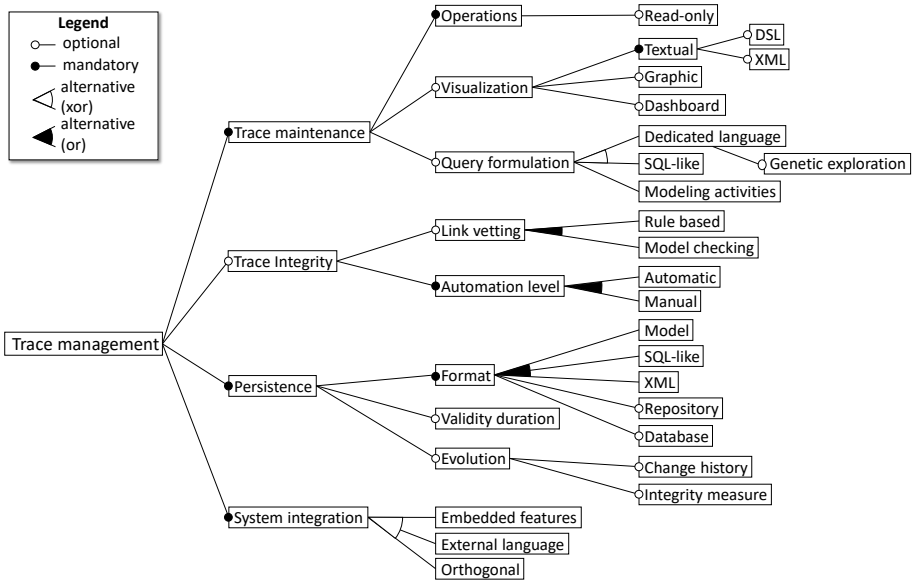

Fig. 5: Tool support for traceability management.

Trace Maintenance Trace links may be affected by changes on the artefacts they link (directly or transitively) and therefore can easily become obsolete. This gradual decay must be seriously taken into account to avoid having to re-elicit traces every time they need to be analyzed. A manual maintenance is not always impossible but not typically feasible in practice due to the amount of information such inspections would involve. Co-evolution techniques [64, 26, 80] attempt to tackle the burden to maintain trace links up-to-date [88, 19].

Beyond being able to manipulate traces, we also need to offer proper ways to visualize and inspect them [29]. The use of graphical representations stimulates human perception and the integration of such technique in traceability frameworks is a useful feature to augment user awareness [42]. On the other hand, matrix-based views offer a valuable perspective to understand and analyse traces [53]. They are particularly efficient in assisting the visualization of coverage characteristics of traceability [32, 82].

In parallel, allowing a rich formulation of queries to assist the exploration of existing traces will help with reducing the amount of information users need to navigate through [19]. More precisely, structured text, in the form of metamodel instances or XML sheets allows query-based mining of trace datasets [24]. Interaction wise, hypertext links is a *de facto* standard to browse trace links. Indeed, following links through successive clicks has become almost natural. Querying relies on the type of representation of traceability artefacts: SQL-like languages benefit from a long history of information mining while dedicated languages offers better legibility. Genetic programming has also permitted the automation of query formulation [77].

Trace Integrity To cope with the decay and volatility mentioned above, ways to determine the integrity of existing traces are greatly needed. Work on these questions, although called out loudly by literature studies, is scarce in practice [101, 5]. The first option is given with manual annotation or vetting of trace links to inform about their level of reliability. Annotations allow a qualitative and quantitative evaluation [18]. This is the case for back-propagation of verification and validation results between design and requirements [41]. Some approaches enable the definition of invariant rules while manipulating traces or their targets [19]. If the invariant is violated, an exception for that trace is automatically generated. For example, we could define a rule that is violated when a change occurs in an artefact targeted by a trace if the corresponding link was identified more than two versions prior to the current version. In the same vein, Heisig *et al.* tag trace links when their target (or source) artefacts are modified or deleted [42]. Thanks to the ubiquitous integration of the tool, warning is raised consequently in EMF.

Trace persistence Many different storage alternatives exist for traceability artefacts. An option is to use SQL-like grammar to store and retrieve traces with the power of database tooling, or to use XML documents to represent trace matrix in a transformable format [57, 27]. The industry uses a lot of informal format and link representations often remains implemented in spreadsheets, text files, databases or requirement management tools. These links deteriorate quickly during a project as time pressured team members fail to update them. Researchers aiming at a reusable approach favour model-based representations able to express specifically defined concepts related to traceability (often in a specific domain of application). The burden of maintaining traces coherent is eased in model-based solutions [21].

Another concern lies in the recording of trace evolution. The trace creation should be recorded, with the successive changes that affect it, for evolution analysis. Integrity measures respective to evolution events (*e.g.,* creation, modification) should be recorded as well to evaluate their evolution during a period of time. Rahimi *et al.* ensure the co-evolution of artefacts and traces [80] using a set of heuristics coupled with refactoring detection and information retrieval technique to detect change scenarios between contiguous versions of software systems.

System integration Like most of the MDE approaches, Helming *et al.* use the same modeling language for both traceability and system artefacts [43]. Tracing features are embedded in the language. The conjunct use of EMF and a dedicated traceability metamodel (both written in Ecore) facilitates the integration of traceability features including graphical versions to stimulate human perception and standard analysis of traces in native environment. Galvao *et al.* in their seminal work on traceability and MDE call for more loosely coupled traceability support that can integrate external relationship with independent representations (in another, ideally common language) [31] as also elaborated by Azevedo *et al.* [7]. Finally, the SysMLv2 implementation committee is calling for *orthogonal* implementation of features such as traceability, annotations and comment through meta-level libraries in order to keep concerns separated at design level.

6 Discussion

The feature model is a first step towards the shared understanding of all dimensions involved in a traceability solution. Ideally, a company interested in a certain set of such dimensions could try to create its perfect traceability solution by combining the top solutions for each dimension. But this is not yet a real possibility as those solution would be difficult to combine and, more importantly, several of the features in the feature model do not really have a great solution yet. This section elaborates on this discussion by presenting some open challenges in software traceability research.

Common traceability metamodel. We have counted over 20 different traceability metamodel proposals. Nevertheless, some are solutions limited to the specific problems the authors present as case studies. And these metamodels are rarely reused, if ever. This proliferation is a challenge to make different traceability solutions interoperate. The research community should agree in a unified proposal that facilitates the composability of traceability solutions.

Security of trace data. Considering that traceability is a major aspect in certification and other critical applications, it is surprising to see so little interest in security concerns in relationship to trace artefacts. We believe security mechanisms (even simple rule-based access control) for traceability are needed to control who can modify what trace data, given the implication such changes can have.

Library of trace types and semantics. We already mentioned the importance of having a rich set of types for traces to let engineers express the reasons behind the creation of a given trace. But at the same time, complete freedom makes reusability of analysis techniques difficult. We would like to see a rich yet predefined set of types for traces that could then be imported in new traceability projects.

Usefulness of identified traces. Managing a large number of traces is time-consuming. As such, we should make sure every explicit trace is actually useful. So far, algorithms aimed at automatically identifying traces are compared based on standard properties like precision and recall. But they should be evaluated on "usefulness": are those traces useful for the end-user? or are they simply redundant noise?

Verification, validation and testing of traces. Our ample literature on verification, validation and testing methods for software engineering should be extended to deal with trace data, especially from a temporal perspective, where temporality and trace decay would depend on pure timestamp values (i.e. how long since the trace was created) and on evolution lag (i.e. how many times the linked artefacts have changed since the trace was created). Reasoning on outdated and potentially incorrect trace data could have strong damaging impacts on the system as a whole. So far, very few approaches target these aspects except for the problem of coevolution in model-driven engineering. A recent study shows that the ability to justify — with evidences and uncertainty evaluation — the quality and integrity of traces is a prerequisite to robust and reliable traceability [9]. And given the effort required to create traces in the first place, it is important to instill more confidence to practitioners unsure if creating traces is worthwhile.

Traceability as core concern in general languages. Another important step towards the mainstream adoption of traceability in industry is the integration of the common traceability metamodel in popular modeling languages like UML or SysML, in the form of a profile (to be able to directly reuse existing modeling tools available for those

languages) or new packages in the respective standards. This way, traceability would become a core concern and a primary class modeling primitive in software development while still being a rich concept and not just a variation of the simple generic plain dependency relationship we can use right now in those languages.

Working together with the industry. Orthogonal to all the others, we (the research community) should aim to have more frequent exchanges with practitioners to better understand why they end up creating traces manually instead of trying to reuse any of the dozens of existing solutions covered in our survey. Some reasons have been already hinted in this paper, based on our own experience in industrial projects involving some type of traceability need and based on the survey we have conducted, but there could be others we are not aware of. Or a different prioritization than the one we have in mind. If we want traceability research to transfer to industry, more and better communication flows should be part of the agenda.

7 Conclusion

Our survey reveals a continuous interest in traceability even if, often, it does not have the spotlight it deserves given the key role it plays in a good deal of software engineering tasks [4]. Work relating to traceability is indeed disseminated within established research communities (e.g., debugging, SPL). Existing conceptualizations vary greatly depending on the community to which its authors belong to as well as the objectives they aim at. As a consequence, a clear and measurable idea of the costs and benefits to software traceability is slow to emerge. To help visualize, classify and compare the different traceability approaches, we propose a feature model covering all important traceability aspects, as derived from a thorough analysis of the traceability literature. Following the existing body of work, we put special emphasis in separating how traces are represented from how they are identified and managed.

Beyond the feature model, our analysis highlights several limitations of current traceability approaches that should be further developed. We believe advancing on those aspects is especially important, even more given the new traceability challenges posed by the growing use of AI in Software Engineering (e.g. in terms of reproducibility and explainability of the AI decisions) [90, 99]. In this sense, we hope this paper serves as a "wake-up call" to make sure new AI for SE proposals come together with a proper traceability mechanism that assists engineers in evaluating and understanding the impact of the new AI components in the software engineering process instead of having to blindly trust them.

As further work, we plan to start working on the above-mentioned aspects starting with a collaboration with some of the authors of other proposals to map and bridge their algorithms and techniques to our modular and quality-focused metamodel in order to combine the benefits of a unified and generic approach with those of a more domain-specific representation. We will also study how better embed traceability concepts into mainstream modeling languages (like UML or SysML) to further facilitate its adoption.

[4] As an example, ICSE'18 awarded a trace-based paper as the most influential paper in the past 10 years [49]. The work introduced a novel trace-based approach to debugging. Though the focus was on the debugging aspect of the paper, traceability was the key to achieve that debugging improvement. The word "trace" alone is mentioned 46 times in the 10 pages paper.

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