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APPLICATION FRAMEWORK FOR TRACEABILITY OF ENGINEERING INFORMATION

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ABSTRACT

The work reported here builds on the TRaceability of ENgineeringINformation - TRENIN (www.trenin.org) project by discussing the the application framework for engineering information traceability. Traceability as a property of the product development should provide a context by which the engineering information evolution can be better interpreted. In the TRENIN project context is explored from two different viewpoints. The first is the context of capturing engineering information evolution including the recording and explanation of the conditions around design activities. The second is the context of using recorded engineering information traces as a basis for identification and understanding of the captured engineering information evolution. Prototype TRENIN application framework is presented consisting of: Traceability Engine, Utilisation Explorer and Visualisation Tool. Results of the framework validation and feedback from industrial partners are discusses and based upon this experience, further research directions are defined.

Keywords: engineering information traceability, traceability ontology, semantic traceability record, information evolution visualisation, TRENIN

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1 INTRODUCTION

Information processing can be considered as an aspect of the dynamics of system that is needed to perform its functions and thus achieve its goals and accomplish its mission (Kampfner 2011). In complex systems such as modern R&D organisations information is processed in a manner that is greatly influenced by the dynamics of design process organisation and implementation. As the variability of information processing increases during the development process, the versatility in which the information needs to be processed increases as well along with costs and complexity of information processing. To be adaptable the R&D organisation needs to have a potential for uncertainty of behaviour at least as proportional as the potential for uncertainty of behaviour of its environment (customers, supply chain, market, etc.). Since information processing is an aspect of the behaviour (i.e. dynamics) of a development process, it must meet the requirements imposed by the variability of this dynamics.

Accordingly to the definition provided by Arthur in 2009, information evolution is driven by information transformation process where all information objects composed of information fragments are related by ties of common descent from the collection of other information objects. In studying information evolution, there is a need to take into account the dependencies between informational content and context and the cognitive dynamics in order to systemically link information evolution to knowledge creation, learning resistance, information overflow, selective processing and innovation (Hicks et al. 2002). Consequently, as the development process proceeds, the information originating from various sources are captured and formally recorded in variety of information objects as for example requirements specifications list, technical reports, meeting minutes or CAD models. To provide control and to ensure reusability and adaptability of the information, the information objects evolution require interactivity and means to be managed - traced, explored, unequivocally interpreted and easily understood (Štorga et al. 2011a).

An application framework for traceability of complex information evolution in the product development process reported in this paper is built as a part of the TRaceability of ENgineering INformation – TRENIN project (www.trenin.org) (Štorga et al. 2011a, b). To accomplish information evolution traceability, TRENIN research resulted with development of semantic traceability records as network of traceability elements and objects interconnected by links of different types and strengths (Pavković et al. 2011, Štorga et al. 2011a, b). The organic visualisation (Stanković et al. 2012) is in the TRENIN project applied as a method to display emerging complex semantic structure of traceability record. The results presented in this paper are focused to discussion on validation results of the traceability application framework developed for utilisation of the semantic traceability records with a goal to facilitate cognition and understanding of engineering information and knowledge structure evolution and support stakeholders to deal with previously described characteristics of the product development process.

2 BACKGROUND AND RELATED WORK

During development process, participants apply considerable knowledge to develop structure and desired behaviour of a designed system and form these cognitions into informational design models diverse in detail and abstraction level. The engineering information represented in design models originate from different engineering disciplines and scientific methods, natural principles, information about existing solutions, norms and regulative, standard components, material properties catalogues, manufacturing datasheets, etc. Multiple software tools are used in different activities at various stages of design process for creating and modifying engineering information. Unfortunately, most of these tools are not fully consistent with theoretical models of design and development and thus provide incomplete information records and, additionally increase the complexity of development process.

One of the challenges for the effective knowledge and information management in design is efficient acquisition of dependency structures for the relevant domains of the complex systems (Lindemann et al. 2009). The multitude of entities and possible dependencies in complex system requires a methodical information acquisition that encourages stakeholder not to forget or neglect relevant information content and context evolution. Additionally, information quality and correctness must be assured during the acquisition process and the acquisition method must be applicable to team work, and once determined, agreements and decisions concerning content and context have to be clearly documented.

The knowledge acquisition and reuse in design practice is often ad-hoc and the designers often consider the time and effort needed to locate the information and investigate information usefulness as too costly, often resulting in little or no attempt at reuse (Kim et al. 2007). In the design environments that have little or no experience with knowledge management systems, designers often find those processes too obtrusive and time consuming, with small benefits for them. Ahmed and Wallace (2003) tried to identify concepts of the taxonomies required for indexing design information and knowledge. Mohan and Ramesh (2007) define knowledge integration as the synthesis of specialised knowledge that is distributed across different artefacts and phases of product development into situation specific systemic knowledge. Brandt et al. (2008) developed the module that comprises concepts for structuring traces recorded during design process execution. Knowledge and information traceability framework for requirements based on formal language for enterprise architecting is presented by Engelsman et al. (2010). Design Rationale Editor (DRed) has been reported to be in successful use by industry to capture rationale and dependencies in complex design Eng et al. 2011). DRed uses directed graph representations, with a simple fixed rather than extensible design ontology and manual layout of of the DRed graphs for visualisation of the recorded content and context.

Utilization of recorded knowledge is a complex area with many still not clear issues and challenges. Hicks et al. (2002) emphasize that reuse of knowledge is frustrated by semantics. The knowledge may not be structured and specific, and for the particular application may require an altered perspective. Here the individual must dynamically step from knowledge back to information and then generate another perspective which may provide knowledge for the new or unfamiliar situation. McMahon et al. (2002) introduce a user interface based approach to the browsing of hierarchically organized information entities that avoids problems of word or phrase search. Kleinsmann et al. (2010) consider knowledge integration as important factor in collaborative product development and that the quality of the collaborative design project is highly dependent on the process of creating a shared understanding.

The traceability approach and methodology proposed in TRENIN project relies on semantically rich product development ontology, which has the central role in information interpreting, defining context, establishing relations, and enabling indexing and searching mechanisms. By utilization of ontology-based model the semantic relations are used as a key mechanism to relate information content with complementary contents, thus pointing in utilisation to additional knowledge that would otherwise remain undetected.

3 TRENIN METHODOLOGY AND SCENARIO

3.1 Traceability records and engineering information objects

The approach that was chosen to be followed in TRENIN project offers semantic traceability record as the means for complex systems information dependency modelling and acquisition (Štorga et al. 2011a). Semantic traceability records are the core of the traceability framework and are defined as network in which nodes represent context for information objects among which traceability is established by semantic relationships of different types and strengths. Related to the development process, the several types of (business) information objects (records) that an enterprise should store information in and about could be specified (Helms 2002):

1. Organisations need to store information about their processes including design process; therefore a process/activities flow information object type should be included.
2. Organisations require resources, e.g. employees and tools to execute these processes. Therefore, a resource information object type should be included.
3. The main outcome of the design process is the definition of the system. Therefore, a project/system information object type should be included.
4. The designed system is described using documents and therefore a document object type should be included.

The four types of information objects interesting for design practice could be explained using an example from industrial partners that participated in our research (see Table 1). The idea behind the semantic traceability records is to identify the physical and abstract concepts and semantic relations from the complex system development process domain relevant for articulation of information objects content and context evolution (Štorga et al. 2011b). The strategy for using semantic traceability records in traceability framework is based on the idea of a highly customizable support system that allows at the same time the capture of traces between activities and events going on in the underlying development episode and the capture of information objects evolution created or managed as results of those activities and events.

Table 1. Object and information types examples (based on the Helms 2002)

Information object	Content information	Relationship information	Life cycle information
Project/ product	• CAD drawing • Change request	• Bill-of-material • Order and order line identification	• Version 1.0 • Status: development • Owner: product manager
Process/ activities	• Assembly instructions • Activity lead time	• Actual input documents • Order identification	• Version 2.0 • Status: completed • Executed by: designer
Resource	• Performance description • Location information	• Current subordinates • Current projects	• Authorisation level • Hours spent on project
Document	• User guide • Target group description	• Brochure and sub document structure • Related products in a family	• Version 6.0 • Status: Published • Change date

3.2 Traceability methodology

The traceability methodology implemented in TRENIN project presumes relevant subset of the traceability ontology is selected in particular organisation, expanded by adding instances of concepts accordingly to the traceability needs of specific organisation, and set of traceability record (TR) templates is created that could be used for specific traceability episodes. In TRENIN project the Merged Ontology for Engineering Design (MOED) was adopted (Ahmed and Štorga 2009, Štorga et al. 2010) as a top level ontology. Traceability events as the driving execution mechanisms of the traceability episode are managed by external engineering applications (e.g. for PLM systems new, release, approve, update, delete etc. events on the information objects) or are generated manually by the different actors (human or software agents) during the design episode (e.g. add new instance of function, change requirement, make decision about alternative, etc.).

Proposed traceability methodology could be additionally seen as an information acquisition framework for the dependency modelling in complex systems design. For the information acquisition, prerequisite is common understanding of the respective relations and domains that are being analysed. Therefore, the semantic traceability records used for the capturing of the context and content of the information evolution in parallel to the on-going design process could provide the formalised source of the complex system and design process description at the different levels of the granularity. In such way, the semantic traceability records based on the extensible and scalable ontology enable customisation of the captured traceability results to the needs of the specific complex semantic network analysis.

The strategy for using semantic traceability records is based on the idea of a highly customizable framework that allows:

- capture of traces between activities and events going on in the underlying design episode, and
- capture of information objects evolution generated as results of those activities and events.

3.3 Traceability scenario

Typical development process is realised in small steps by redesigning the existing systems, rather than by designing entirely new ones. Traceability episode covers a certain time interval of development process and is composed of sequence of traceability events which could be understood as set activities/actions in design process, usually prescribed within enterprise with different granularity. Traceability relevant data should be recorded in semantic traceability records when event associated to the objects that are subject of tracing happened in particular point of the traceability episode (Figure 1). Utilisation of the resulting complex dependency structures of traceability records (Pavković et al. 2013) which emerge from different concepts and semantic relations, calls for a usage of suitable analytical technique to convey the relevant meaning expediently. The visualisation technique that was selected during implementation enables more effective navigation and browsing among recorded traceability content and to explain engineering information in right context in which it is supposed to be captured, explained, understood and reused.

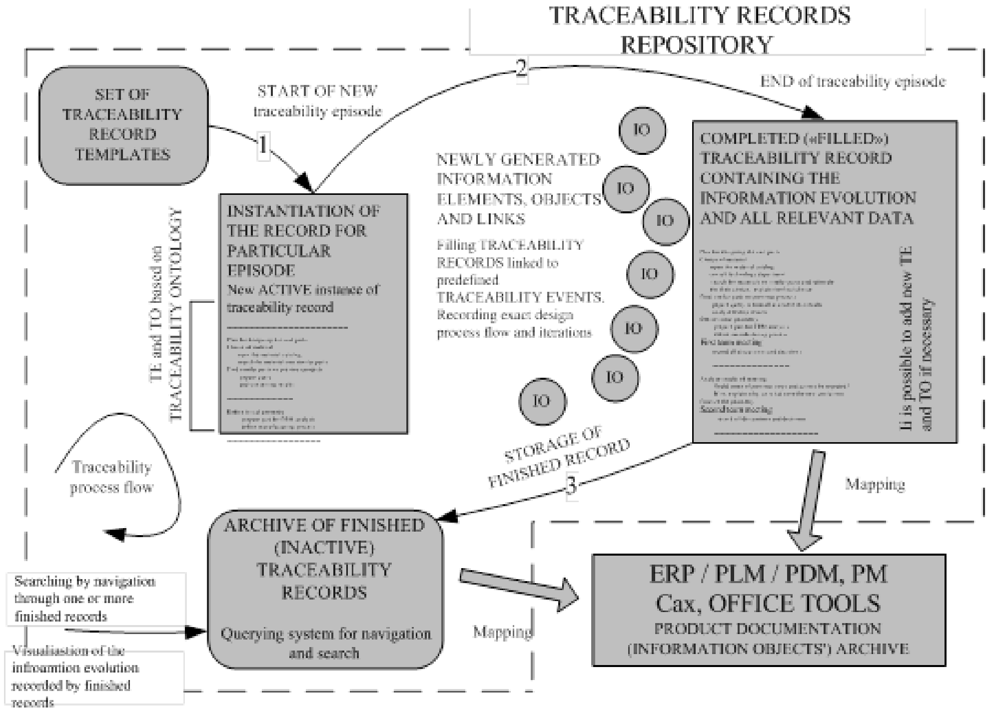

Figure 1.Traceability scenario (Pavković et. al 2013)

Traceability framework based upon described scenario should consist of two parts:

1. **Identification and recording of the information objects evolution**. The most experienced designers should help in creation of traceability record templates for particular classes of design projects. In such way experienced designers could generate and disseminate the knowledge about how particular design episode should be executed, monitored and managed based on their own experience. When starting a new design episode, the traceability user choose the particular traceability record template containing a set of predefined traceability elements, traceability objects and the associated traceability events. Through the timeline of design episode realisation, the traceability record is being updated, upgraded and "filled" with traceability data as a result of design activities, designers' actions, decisions, reasoning, events on information objects, etc. The result of the design episode is finalised traceability record with explicit information objects evolution routes recorded, explained and documented. Finalised records are being stored in archive and are available for utilisation.
2. **Searching, understanding and reusing information**. By choosing the appropriate active or stored traceability records, the responsible person could start the process of browsing, querying, and searching through recorded and documented traces using traceability ontology as a starting point. This process could be performed on the one record or on higher level - across number of different records. Records contain numerous references to information objects that are being managed by external software tools used during design episodes. Predefined and organized reuse of stored traceability data could be achieved by navigation through traceability records that suggest the user what is (or should be) available for searching and tracing and where this information could be found, e.g.: changes on existing solutions, reusing of the existing solutions for new problems, viewing problems and solutions on previous similar projects, analysing testing reports, understanding choices during decision making etc.

4 TRENIN APPLICATION ARCHITECTURE AND IMPLEMENTATION

The traceability application framework as an integrator of process and product related information that are fragmented across different information objects managed by engineering support tools is described as a main contribution of the TRENIN project by Štorga et al. in 2011b. Rather than just being static and depending on designers responsibility and willingness to fill traceability record when a traceability point is reached, agent based architecture of the traceability prototype application should enable more autonomous, dynamical and robust solution as an addition to the existing EDM/PDM/PLM solutions alleviates the implementation efforts and helps to avoid ambiguous functionality, data structure and redundancy of information. As is shown on the Figure 2, the core of the framework is active traceability engine.

A traceability engine is coordinating agents' activities by creating and dispatching new agents, eliminating unnecessary ones, and maintaining all internal communication including recording the results of the traceability activities in database. Connection to external applications that are managing information objects development (through versions, revisions, states) during design episode is created through the specific interface. The primary task of the external application interface is to capture events in external application and transfer information about them to the traceability engine for processing.

Based upon recorded contents, users could access the traceability record data using querying mechanisms and utilise results of the recorded traceability episodes by means of standardised reports (Pavković et al. 2013) and visualisation techniques (Stanković et al 2012). As described within traceability methodology given in the previous section, each of the graph's nodes (see Figure 3) may represent traceability record (TR), traceability element (TE) or traceability object (TO). It is necessary to stress out that traceability record comprises of the instances following the traceability ontology, meaning that there exists a type graph with its own relations and entities defining the traceability entities and allowing the application of various semantic filters. Thus the nodes of graph are labelled and coloured accordingly to be distinguishable. The semantic relationships are established as directed edges and labelled as allowed by the underlying traceability ontology.

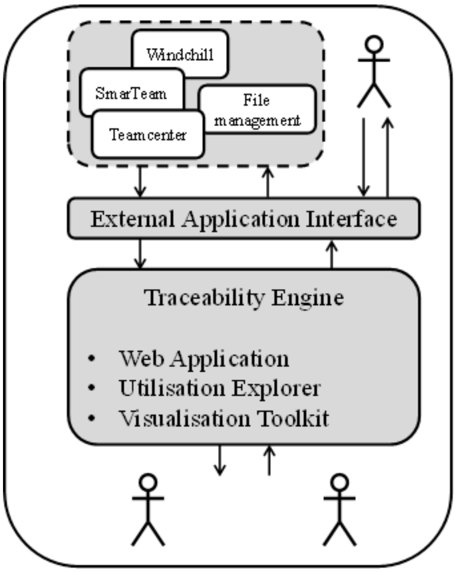

Figure 2. TRENIN framework architecture

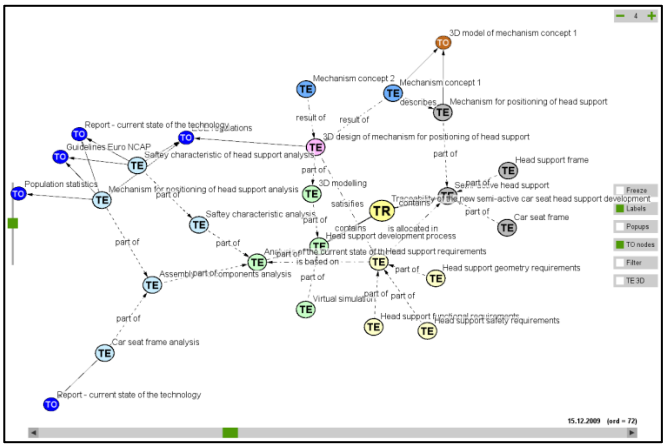

Figure 3. Screenshot of the traceability record (TR) visualisation

To produce organic look alike a force vector/fluid damping graph relaxation algorithm which maintains attractive force between linked entities and results in spring like oscillation effect when the act of two entities' being connected occurs. The overall emerging effect occurs when establishing links results in clusters formation within graph's structure since the linked nodes move close to each other under the attractive force effect. The network formation observed in time either shows the context evolution when considering information object (TO) or can show the evolution in the understanding what a is a concept defined in terms of TE's. Thus, traceability records should not only help to trace information objects related to the system being designed (product information), but should also enable traceability on the activities on related information objects (dependencies) to maintain understanding of the information objects evolution context (process information).

Starting from the single node representing a TR user will have to navigate through time line (evolution slider at the bottom of the screen) to inspect the evolution of TE (defining context) and TO (defining content) based upon the traceability events (result of the undergoing design process). The input to visualisation is provided by TRENIN system as a result of dynamic query on recorded traces. Start and stop points of traceability episode are relevant only for traceability record, and all of the other entities of the graph became adjunct or created a new and then adjunct to traceability record within that time frame. To augment the visual analysis of information dependencies even further, a 3D matrix view of directed label multigraph is being provided as well. To be able to inspect multiple connections that might arise between traceability entities in respect to available domains in predefined ontology, the 3D matrix view, i.e. the adjacency matrix, is realized with each domain posing as a "slice plane" of a parallelepiped. The parallelepiped is defined with its base as traceability entities over traceability entities rectangular mesh and its height as spread over all possible relations. Thus, the planes displayed as rectangular meshes and relations as fillings of these meshes are made to appear semi-transparent and allow full navigation in 3D to enable better overview. At the moment only the top view with distribution of relations among entities of the traceability record is being supported. The 3D matrix view supports the time navigation as well, which enables to show the dynamics of dependencies growth in the matrix view. Figures 4 and 5 present a 3D matrix view of the traceability record's graph at the end of a traceability episode. Both the full 3D matrix and its corresponding orthogonal top view of semantic relations are being shown.

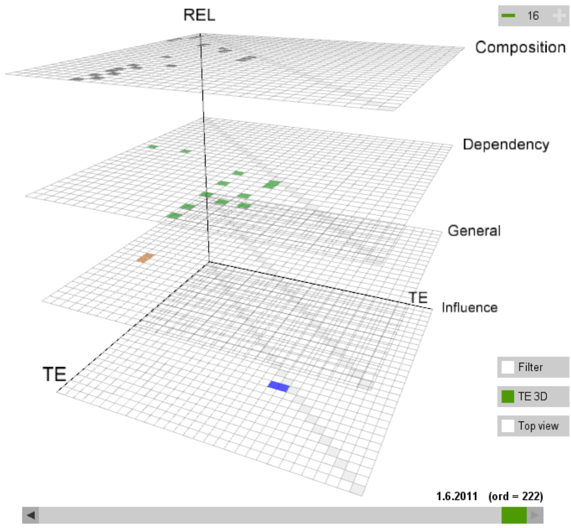

Figure 4. 3D matrix view – perspective

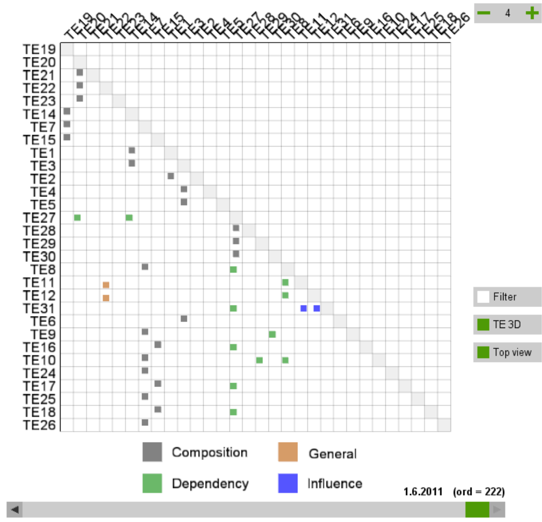

Figure 5. 3D matrix - top view

The developed interactive visual exploration environment relies on various computer graphics effects like colour, shape, highlighting or animation, and user interaction. Application of various layout algorithms and semantic filters to display recorded and stored complex structure of traceability record should help in identification and analysis of information evolution patterns. Filter application examples in the graph view mode are shown in Figures 6 and 7. Traceability objects, i.e. text documents and CAD models, which are relevant for selected viewpoints (i.e. conceptual design, decision making) are shown as filtered out. The uninteresting sub-structures of traceability record are tinted to emphasise the relevant content.

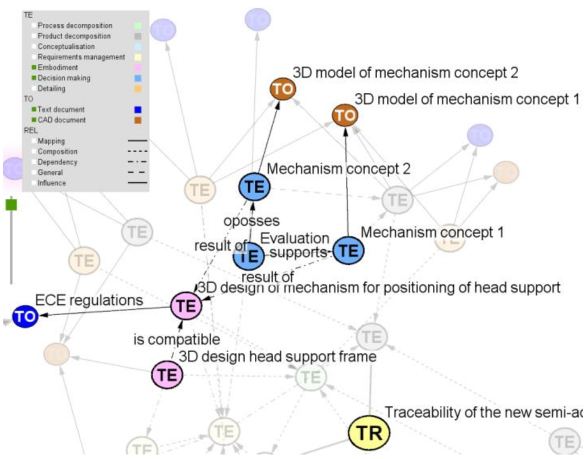

Figure 6. Filtering decision making and embodiment viewpoints

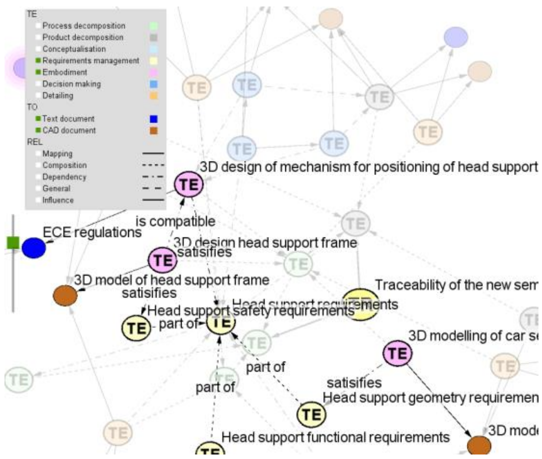

Figure 7. Filtering decision making and requirements management viewpoints

5 DISCUSSION ON VALIDATION OF THE PROPOSED METHODOLOGY AND TOOLS

The development projects from two industrial partners on design of the mechatronic systems for automotive, energy and transportation sector were selected for validation of the methodology and prototype system:

1. **Test case 1 – development of new vehicle control system for trams/trains.** Vehicle control system controls all electronics units in the electrical vehicles. It is responsible for control, measuring, sequencing, protection, supervision and communication. For the purpose of the traceability method validation several traceability record templates for early development phase with goal to trace consolidation of design project and design requirements during development of the new variant of the system and traceability record templates for late development phase with a goal to trace the process of hardware and software subsystems testing after integration have been created and used.
2. **Test case 2 – development of new generation of vertically self-adjustable head support for car seats.** Ergonomically designed car seat head support encourages a relaxed sitting posture and can help with neck pain relief, low back pain, tension and fatigue for driving. The car seat head offers firm support and promotes a relaxed posture improving driving comfort as well as car seat safety. For the purpose of the traceability method validation, several traceability record templates for design project with goal to trace execution and implementation of the safety guidelines and norms into components and traceability record templates for embodiment and detailing phase with a goal to trace key product characteristic realisation in order to ensure the quality of the solution accordingly to the requirements have been created and used.

As a guideline for validation, the work on factors that influencing traceability in organisations recognised by Öberg (2012) were used and specifically considered in our work. The validation goals were defined as:

- to create and execute traceability records based on the extension of the traceability ontology for particular company and encourage designers to trace specific engineering information evolution to proof methodology applicability,
- to identify and define key filters and queries for complex information content and context browsing in the utilization phase, and
- to test visualisation approach in order to support understanding of the information evolution during design process.

Validation process has shown that good understanding of the design process and description in the form of the traceability episode scenarios is main prerequisite for the successful implementation of the traceability methodology. For the main business processes in well organised manufacturing enterprises with a detailed workflow (where each step includes detailed description of inputs – what, who, activities, and outputs – what, to whom) it is easy to define traceability record templates. Using the known procedures of the backbone process enables traceability users to understand in advance what, when, how and why should be recorded in order to achieve traceability.

As the main advantage of the presented approach, validation confirmed contextual richness of the traceability records with possibility, in a perspective, to become a base for advanced reasoning on recorded traceability routes. The main problem in the same time identified during traceability execution was required manual work and interaction by the user in cases that something beside the content of predefined templates should be recorded and when automatic tracing was interrupted.

They were also some additional issues pointed out by industrial partners during test cases execution. The first one identified was practical usage of presented approach, specifically the amount of traceability data that should be recorded in order to enable traceability of information objects evolution. Early phases of the design process were of most interest since they represent the ideation phases of the whole design process. Most often the ideas generated within a creativity boosting sessions like brainstorming, or a project team meetings are neglected and misplaced thus being not usable for future projects. The test traceability records enabled such information after being structured accordingly to the context of the company.

The second issue that was pointed out by industrial partners was level and granularity of traceability for particular case. It was founded to be supported by TRENIN application framework through possibility to select traceability levels by extension of the proposed ontology for particular case. Of course, traceability at the most detailed level vs. maintenance costs is key question for successful implementation in daily practice (this could be verified after few more implementations in the long term usage in daily practice). In addition, possibility to select the specific time periods during utilisation was helpful in order to recognise patterns of understanding.

The third important issue that was considered during the validation were influence factors originating from the current practice and could be seen as source of the obstacles to the successful implementation in daily work. The biggest problem was lack of understanding of the traceability needs related to the current working practice from the top management to the designers. Organisational culture, rigid requirements of the quality systems and integration with the existing tools used in daily work were pointed out during validation as a main field where additional effort should be invested during implementation. Very helpful in resolving this issue was reporting and visualisation of the finished traceability episodes showing in new way the evolution and dynamic of the traced design process.

At the end of validation, industrial partners concluded that the main selling point of the proposed TRENIN methodology and prototype application is combination of the two:

- Pro-active approach built on assumption that in order to trace information objects evolution over a long time span, it is necessary to prepare strategies and solutions in advance (ontology specific or the organisation, templates of the records, predefined metadata set).
- Dynamic of the undergoing product development and design process in the same time requires ability to continuous alter the traceability records (interrupt state, possibility to add elements, objects, relations) what was also enabled.

6 CONCLUSIONS

If we look at the TRENIN project aim set to increase knowledge about what is required and how to achieve traceability of engineering information evolution over the time, we could conclude that it is successfully answered by:

- Proposal of the traceability methodology based on the traceability ontology and semantic traceability records
- Development of the traceability framework application for capture and utilisation of the engineering information object content and context evolution in engineering environment
- Validation of the methodology and prototype application based on the test cases provided by industrial partners and in cooperation with them

Test cases and validation showed that the industrial partners' capacity to achieve desired level of traceability was improved through the project by:

- Extending the awareness of the need for traceability in order to improve the quality of the product development and design process by education of the employees through workshops and discussions during interviews
- Showing how the current procedures and tools used in the daily work could serve as a starting point to improve traceability of the information evolution through their implementation in a form of the semantic traceability records and their utilisation

We could also argue that scalability of the results could be justified by the following. Project was conducted in environment of the two different industrial partners:

- Massive production of the subsystems for the automotive sector
- Individual production of the subsystems for the energy and transportation sector

Therefore, it is reasonable to argue that proposed methodology based on the extendible ontology as a base of the semantic traceability record, could be ported to the other type of enterprise systems and information transformation processes (public sector, processing industry, services, etc.). At the moment authors are working on implementation of the present approach to the organisational knowledge structure evolution in international non-governmental organisation based on the emails exchanged on the issues related discussion lists.

However, confirmation of whether or not the TRENIN methodology and application can improve organisation's capacity to achieve the desired level traceability is difficult task at the moment. Therefore, deep reflection on TRENIN usefulness could be provided only after serious period of using the TRENIN results in daily work.

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