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REFERENCE MODEL FOR TRACEABILITY RECORDS IMPLEMENTATION IN ENGINEERING DESIGN ENVIRONMENT

Mario Štorga[1], Dorian Marjanović[1], Tomaž Savšek[2]
(1) University of Zagreb, Faculty of Mechanical Engineering and Naval Architecture, Croatia
(2) TPV d.d. Novo mesto, Slovenia

ABSTRACT
The work reported here builds on the framework for engineering information development traceability by discussing the traceability records implementation within engineering environment. The four key processes in the product development practice (requirement-, change-, characteristic-, and decision management) have been considered in more details as a basis for the development of the traceability records reference model. Reference model for traceability records represents dynamic container of the traceability elements, information and links semantically enriched in order to provide the context of the information objects development. The further steps in TRENIN (www.trenin.org) project progression have been identified and described.

Keywords: TRENIN, traceability records, engineering information development, reference model, merged ontology for engineering design (MOED)

1 INTRODUCTION
In order to master challenges of the modern manufacturing paradigm and confront with the challenges of the complex products and services, companies have recently developed new approaches for reusability, adaptability, and variety of products, services and engineering information. The importance of engineering information is underlined by the fact that product lifecycle viewed as chain of information transformation processes both consume and create large amounts of information [1]. During the different stages of the product lifecycle different participants will acquire information from many sources, such as handbooks and design guides, catalogues, journals, books, training courses, previous projects, discussion with colleagues and customers, user and service guides, disposal reports, etc [2]. As the product lifecycle proceeds, engineering information will be used to document the decisions taken, describe potential limitations of existing solutions or their suitability for adaptation, and to identify what further information is needed. Throughout this process, the information will be evaluated and recorded by members of the product lifecycle team in a variety of formats, such as sketches, drawings, notes and meeting minutes. In order to support the product lifecycle as it progresses, a proportion of this information will be formally recorded in technical reports and other engineering documentation, such as CAD models, production drawings, calculations, installation instructions, user guides, etc. It can therefore be argued that the efficiency of the product lifecycle process is highly dependent on the effective utilisation of the engineering information.
Traceability of information provides the basis for assessing the credibility of engineering information, its better understanding and making judgments about the appropriateness of its use for a particular task [3]. Information traceability is considered as a quality attribute and many international standards require the creation of traceability procedures. In order to fully understand information it is necessary to understand the circumstances in which it has been developed and recorded. Currently there is little provision for acquiring, capturing and delivering with the engineering information, the information that provides its development context, and few tools to support this process [4]. The objective of our project is to develop an approach to integrate and trace information fragments stored in diverse engineering working environments in order to support product development process. The work reported here builds on the **TR**aceability of **EN**gineering **IN**formation - **TRENIN** (www.trenin.org) framework for engineering information development traceability by discussing the issues, perspectives and reference model for traceability records implementation in engineering design environment.

2 TRACEABILITY OF ENGINEERING INFORMATION DEVELOPMENT

The stakeholders with different roles in product lifecycle process need traceability carried by traces of the product lifecycle routes, because they want to reuse existing engineering information along sources, references, evaluation, meaning, reasons, arguments, documentation, choices, critique, consequences [4]. They would like to leverage all relevant information no matter where it originated, no matter what its format, and no matter where it resides in order to help their organization innovate, compete, provide service and grow. Ability to trace engineering information development becomes prerequisite for better information value understanding and recognition and act on the importance of information quality in product lifecycle process [5].

Little is currently understood about the requirements for engineering information traceability in product lifecycle and there are few methods by which effective traceability can be ensured. There are a number of methods and tools which contribute partially to the traceability of information development in general, but the emphasis here is either on product data management or project/workflow management rather than the explanation of development and rationale on information fragments. Functionality that is missing in exiting engineering tools from the information traceability viewpoint is summarised in following table.

Table 1. Functionality relevant for information traceability that is missing in engineering tools

EDM/PDM/PLM tools	CAD tools	OFFICE tools
• Information fragments management • Versioning mechanism for the information objects that doesn't have a physical or digital file • History management of information objects attributes • Semantic relationship between different information objects and information fragments	• Track changes on content development • Information fragments management • Change context and rationale management • History management of feature properties	• Change context and rationale management • Information fragments management (structure and properties) • Track changes feature in all office tools (not only in text processors)

Traceability should enable understanding the semantic relationships that exist within and across information objects containing information fragments about requirements, concept explanation, design details, component description, production specification, maintaining procedures, etc. These semantic relationships could help engineering designers to understand the existing information and reuse them in new context. The need for maintaining traces among information objects is documented in our previous publications [3], [4]. Research literature describes the impact of poor information traceability practices on project efficiency. Decrease in system quality, increase in the number of changes, loss of knowledge due to turnover, erroneous decisions, misunderstanding and miscommunication are some of the common problems that arise due to lack of or insufficient traceability of engineering information [5].

The simplest traceability tools that have been found in engineering practice during the interviews with industrial partners involved in TRENIN project are suited only to support simple information traceability procedures for personal use and provide limited support for information objects (IOs) dependency analysis. This led us to the idea of **traceability records**. The

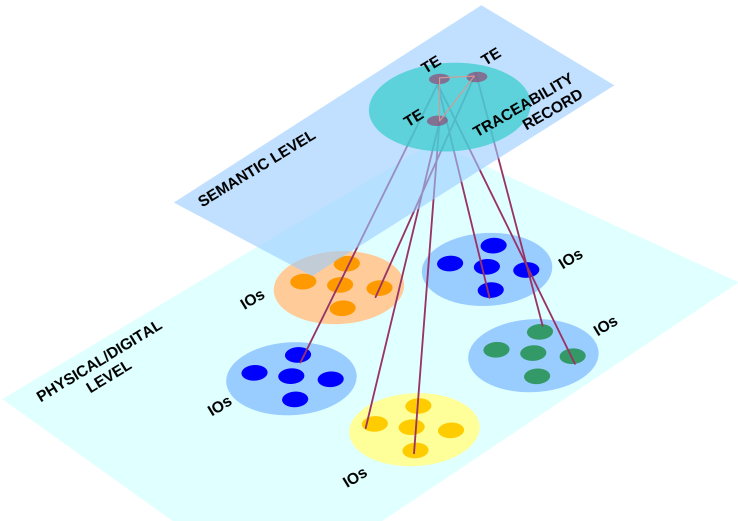

Figure 1. Traceability records

purpose of the traceability records (Figure 1) is to enable traceability on a process and product information that is fragmented across different information objects managed by different computer tools in engineering design environments. Content and structure of the reference model for traceability records and suggestions for implementation are described in the following chapters.

3 TRACEABILITY ISSUES IN ENGINEERING DESIGN PRACTICE

Why is the achievement of engineering information traceability in modern highly-automated product development environments, still so difficult? The authors contend that the reason has as much to do with processes and human factors as with issues of heterogeneous tools and distributed teams. However, the current organisation procedures are not supportive to traceability procedures since people exchange engineering information across organizational and discipline boundaries, they reuse existing information in new and unpredictable contexts and often information is translated from one format to another during which information loss occurs. Furthermore, because of lack of the formal representations of the complex engineering design information, these exchanges still partly occur informally. As a consequence, retrieval of the engineering design information objects (e.g. with respect to format, type, and contents) as well as correct interpretation of its content (due to the specific domain context) is difficult.

The key issue with the traditional and existing traceability approach, in particular from the point of view of industrial applications, is that it is labour intensive, both for the product information-engineering specialists as well as for those whose information they are seeking to acquire. Current approaches and studies give no guidance on which information must be traced and how, which traceability categories are the most feasible, useful and reliable, nor how to assure quality in traceability of engineering information. Therefore, the set of the interviews have been conducted with the representatives of the industrial partners. The traceability idea of a process that is parallel to the undergoing engineering process [3], [4] has been presented in series of the workshops organised for the representatives of the R&D departments of industrial partners in Croatia and Slovenia. Industrial partners are operating on the global market and are recognized as a development and manufacturing suppliers in the automotive industry, energy sector and transportation. Industrial partners have established practices of information management, supported by prescribed procedures and in house developed information tools or commercial PDM/PDM solutions. The interviews have been conducted with representatives of the departments involved in product development processes. As the result of the interviews, the following basic requirements for engineering information traceability in industrial environment have been extracted:

- For each created information object including fragments (definition is provided in [3] and [4]) it should be possible to trace the context of information object life continuum:
  - **Who** and **why** created the information object?
  - **What** are the destinations of the information object life continuum?
  - **What** the "information receivers" should do with the information object?
  - **Where** and **how** long the information object is being stored?
  - **How** is information object related to the other information objects?
- Major identified traceability issues form the management viewpoint are:
  - **What** are the implications on project for each information transaction for one or more information object?
  - **Which** are the information objects belonging to one particular context or viewpoint?
  - **What** is the status of the information object content in particular project milestone regarding completeness and accuracy?
  - **What** are the major business changes in project portfolio, **when** and **why** they happen, and which information objects are affected?

Good examples of the existing traceability practice was found in current business processes that ate prescribed by workflows where each step has a record that includes detailed description of **who** provided particular informational inputs, **what** these inputs were, **who** executed the activity, **what** were the information outputs of the activity and to **whom** the outputs were proceed. In such way, "traces" of activities and related information objects are recorded and could be used for information retrieval and reuse in the new contexts. The previously described procedure works well in engineering practice, but currently it is mostly a mix of "paper work" and computer supported product data and document management.

Main problems and disadvantages related to existing traceability practice recognised at industrial partners are:

- There is no one common platform for traceability procedures and methodology among different departments.
- Existing traceability records are separate files that are not integrated with the existing engineering or management tools.

The consequences of such practice are:

- Only one person could work with and access the traceability record at a time.
- There are many redundancies in content between exiting traceability records.
- There are limited possibilities for avoiding and controlling errors.
- There are very limited search and reuse mechanisms for the recorded content.

The main conclusions from the interviews have been that the existing traceability procedures in current practice (those that were identified during interviews) could be extended and improved in two ways:

- **In their scope -** what part of the engineering process and information granularity should be traced and on what level?
- By extensive **usage of information technology**:
    - To achieve semi automatic or automatic traceability in order to make this task more natural and user friendly for the engineers.
    - To avoid redundancies by integration of traceability procedures with current working procedures and used computer tools in daily work.
    - To develop traceability mechanism for information objects and fragments as addition to current features of the product data and lifecycle management tools (EDM/PDM/PLM).

Lessons learned from interviews and analyses among industrial partners were valuable for development of the reference model for traceability records that represent dynamic container of the traceability elements, information and links semantically enriched to capture the context of the information objects development [6].

4 KEY TRACEABILITY PERSPECTIVES FOR PRODUCT DEVELOPMENT

Traceability can play a crucial knowledge and information management role in product development if the necessary facilities to support traceability are developed. According to literature traceability could assists in understanding the relationships that exist within and across product development information domain [7]. Currently available PDM/PLM systems support information management, especially in the later phases of the product lifecycle which is characterized by more deterministic and well-known processes. However, they lack essential capabilities for the management and use of product information in proper context. Some recent research efforts try to extend the capabilities of PDM/PLM systems for product information traceability during the design process [8]. Such PDM/PLM repository in practice is usually limited to the storage of product data and documents and functionality like document repository, structure and lifecycle management, product repository, structure and lifecycle management, and process repository, structure and lifecycle management.

Participants in the product development process view traceability as providing a link from initial information for product development, for example requirements and the actual product components that satisfy those requirements. By capturing the information how components realize various functions and which requirements are mapped to different components, the engineers would be able to verify results of the product development. In addition, the product compliance verification procedures such as tests or simulations could be developed based on the specific characteristics derived from user requirements. If any engineering change should occur in the product development process, then the traceability should help with identification of the verification procedures that should be redeveloped. A product component may depend on other components and may also interface with external systems. This information could be used in evaluating how a change on component will affect other components and systems. All previously described dependencies, are not currently well supported and captured by supporting computer tools. To further illustrate information lack in capturing engineering information, we could consider the following quote from a user: "*Often we have no idea who made these decisions, and how they impact the rest of the effort. Simply trying to do these at the end of the*

project or after the fact does not work. Often the people who worked on it are gone without a trace, of what happened… not disciplined enough to document these… with all the demands on the team." [9].
In order to define the key aspects for the traceability record reference model, the four key perspectives relevant for the product development practice have been considered thoroughly. Those especially pointed during the interviews with industrial partners are requirements, changes, characteristics and decisions traceability.

4.1 Requirements traceability

Requirements are the subject of an extensive body of literature in the engineering systems domain. Some of the work from this domain has been investigated with a view to making recommendations for traceability of the requirements in engineering design [9]. The requirements traceability needs of different stakeholders – customers, project managers, analysts, designers, maintainers, and end users – differ due to differences in their goals and priorities. The following definition sums up the general view of the requirements traceability: *"The requirements traceability is the ability to describe and follow the life of a requirement, in both a forward and backward direction, i.e. from its origins, through its development and specification, to its subsequent realisation and use, and through periods of ongoing refinement and iteration in any of these phases."*[10]. In requirements definition phase it is important that the rationales and sources of the requirements are captured in order to understand requirements evolution and verification. Modifications during design appear e.g. if the requirements evolve or if the product is developed incrementally. During design phase requirements traceability allows to keep track of what happens when specific request is implemented before a product is redesigned. Traceability should also give information about the justifications and assumptions behind requirements. Test procedures on prototypes can be traced to requirements or concepts and this kind of traceability helps to design and modify test procedures. Modifications after the delivery of the product will happen due to various reasons (e.g. to correct faults or to adapt the product to a changing environment.

4.2 Changes traceability

To implement an engineering change request, change management strategy helps to identify necessary steps and understand the impact of changes. In general, the objective of different change management practices is to ensure a systematic development process, so that at all times the system is in a well-defined state with accurate specifications and verifiable quality attributes. Change management helps in the management, control, and execution of change and evolution of product, while traceability usually helps in managing dependencies among related information objects across and within different phases of the development lifecycle [11]. In vast majority of organizations, these two practices are implemented independently. The lack of knowledge about how the process and product information are related makes it difficult to understand different viewpoints held by various stakeholders involved in change process and estimate the impact of changes, thus hindering change management and adversely affecting the consistency and integrity of the product. Without the capability to acquire and trace engineering information development, it is very difficult to incorporate modifications in the system.
Whereas version control tools are commonly used to manage dependencies between versions of information objects, dependencies among the variety of engineering information fragments arising from product development context like requirements, functions, concepts, test procedures, etc. are not adequately managed. In fact, it is the presence of these dependencies that makes change management very complex. Most of the current models can only manage dependencies between changes and products at the level of documents or users. They are not capable of representing finer-grained dependencies between information objects and fragments.
In summary, results from prior research there is the strong link between change management and need for traceability practices with two main challenges:

- Lack of support for traceability of dependencies among information objects and fragments across different phases of development lifecycle.
- Lack of support for the traceability at a fine-grained level of information granularity.

4.3. Key product characteristics traceability

The definition of key product characteristic is one of the “gifts” of automotive manufacturing to all other kind of production. It is quite impossible to cost-effectively follow and control every possible characteristic of a given product. However, it is possible to define the most significant characteristics as Key Product Characteristics (KPC). For example, the front of an instrumentation cluster may have significant appearance requirements, but is usually not necessary that the back of the product (invisible to the operator) have the same level of appearance quality. Hence, the front appearance and its definition is a key product characteristic. The same idea applies to services where the measurements in the back-end of the process are not relevant to the customer who only sees the front-end of the product. In addition, critical characteristics are defined by automotive industry as product or process requirements that affect compliance with government regulation or safe product function, and which require special actions or controls. In a product FMEA for example, they are considered in a literature as “Potential Critical Characteristics”. Examples of product or process requirements that could be critical characteristics include dimensions, specifications, tests, assembly sequences, tooling, joints, torques, welds, attachments, and component usages. Special actions or controls necessary to meet these requirements may involve manufacturing, assembly, a supplier, shipping, monitoring, or inspection (Figure 2).

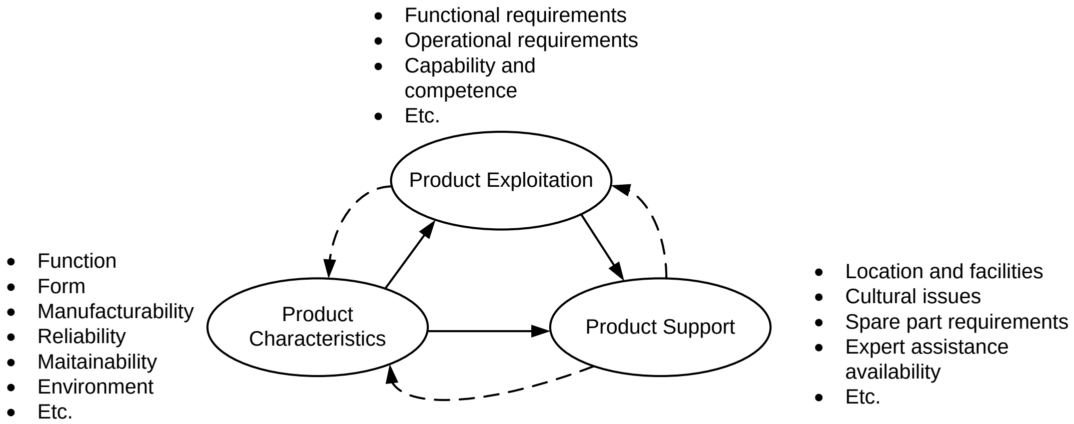

Figure 2. Role of the product characteristics in product life [12]

The KPC could be a feature of material, process or part where the variation within the specified tolerance has a significant effect on product fit, performance, service life or manufacturability [12]. A KPC should be identified only after determining a benefit exists from controlling the characteristic to assure that the feature is at or very close to the specified value. KPC is usually identified as a part of the product development process. Once a KPC has been identified, variation management activities must be performed until the process or processes that influence that characteristic are in control and process capability has been established. Implementation of the appropriate traceability methodology for the key product characteristics could in industrial practice assure continued performance of the products life cycle process.

The purpose of the key product characteristics traceability is:

- To identify characteristics which demand extra attention because excessive variation may affect a products function, safety/compliance, or quality of a product;
- To provide a framework for facilities simultaneous engineering, teamwork and cross functional involvement in product and process design, control methods, continuous improvement and variation reduction;
- To provide insight to the effects of variation on the product and customer satisfaction.

4.4 Decisions traceability

In the complex group decision and negotiation activities, the participants access and use information about the problem and solution domains, which is stored in a variety of information objects such as spreadsheets, meeting minutes, design documents, etc. Seamlessly linking such information fragments spread across organizational work processes and tools will be very helpful in supporting group decision and negotiation activities [13]. Creation of such networks by seamless integration has been attempted by many tools handling explicit, codifiable content (e.g. workflow tools, project management systems, collaborative systems, intranets, and data warehouses) and those that enable sharing and distribution of contextualized information content (e.g. digital whiteboards, case-based reasoning tools, multimedia channels, annotation tools, and concept mapping systems). One of the common problems in facilitating integration of information objects to support collaborative product development is that the stakeholders involved do not have adequate guidance on what kind of information fragments should be integrated, and how the integration should be structured and used.

Traceability, defined as the ability to describe and follow the life of a physical or conceptual information objects, addresses these challenges by providing semantic and structural guidance to objects integration on the semantic level. We could argue that integrating information fragments used by various stakeholders and providing traceability among them will increase the effectiveness of group decision and negotiation activities performed during the product development process.

Information objects traceability network can be defined as a semantic network in which nodes represent different information objects among which traceability is established through logical links of different types. Such a network facilitates the understanding and communication of the context in which group decisions and negotiations are carried out and help in monitoring the repercussions of decisions in the underlying context. Capturing the history of decision making and linking underlying assumptions with the alternatives considered during a group decisions and negotiations activity can provide a dynamic validation of the decisions under varied contexts established by invalidated and new assumptions.

5 DEVELOPMENT OF TRACEABILITY RECORDS REFERENCE MODEL

Traceability reference model is considered in our project as a prototype information model for building traceability record templates. A traceability reference model identifies physical and abstract concepts and relations from the product development domain relevant for description of the information object in the context of the product development process. Prior research suggests that a traceability framework will comprise at least three layers [3], [4], [6]:

- A top level ontology defining the formal language by which traceability reference models for product development could be defined.
- A set of traceability reference models which can be customized and extended within the scope defined by the ontology accordingly to the specific traceability needs.
- A record of actual traces, recorded following the chosen templates.

The purpose of reference models is to significantly reduce the task of creating organization specific traceability records. The idea is that information creators in particular organization selects relevant parts of the reference model, expands them accordingly to the specific traceability needs, and create set of traceability record templates that could be used in traceability episodes. Traceability records should not only help to trace information objects related to the products of development (product information), but should also enable traceability on the activities on related information objects (dependencies) to maintain understanding of the information objects development context (process information). During traceability episode, entities from the reference model – **Traceability Elements (TEL)**, are mapped to the information objects managed by external applications (e.g. EDM/PDM/PLM) – **Traceability Objects (TOL)** like projects, products, documents, items, users, flow processes, etc. **Traceability Events (TEV)** are driving execution mechanisms of the traceability episode and are initiated by the events on information objects managed by external application (e.g. new, release, approve, update, etc.) or are generated manually by the user during the traceability episode (add element, add link, add object, etc.).

5.1 Product related traceability elements reference model

In presented research, we decided to adopt a Merged Ontology for Engineering Design (MOED) [14], as a top level ontology for definition of the TRENIN formal language. The main building blocks of the TRENIN ontology has been decomposed accordingly to the previous discussion as: product related traceability elements, process related traceability elements, traceability links, traceability objects and traceability events. The four key perspectives that have been pointed out in the section 4 have been used for the extraction of the product and process related traceability elements. The product related elements of the reference model are partially shown on the Figure 3 in order to illustrate the reference model.

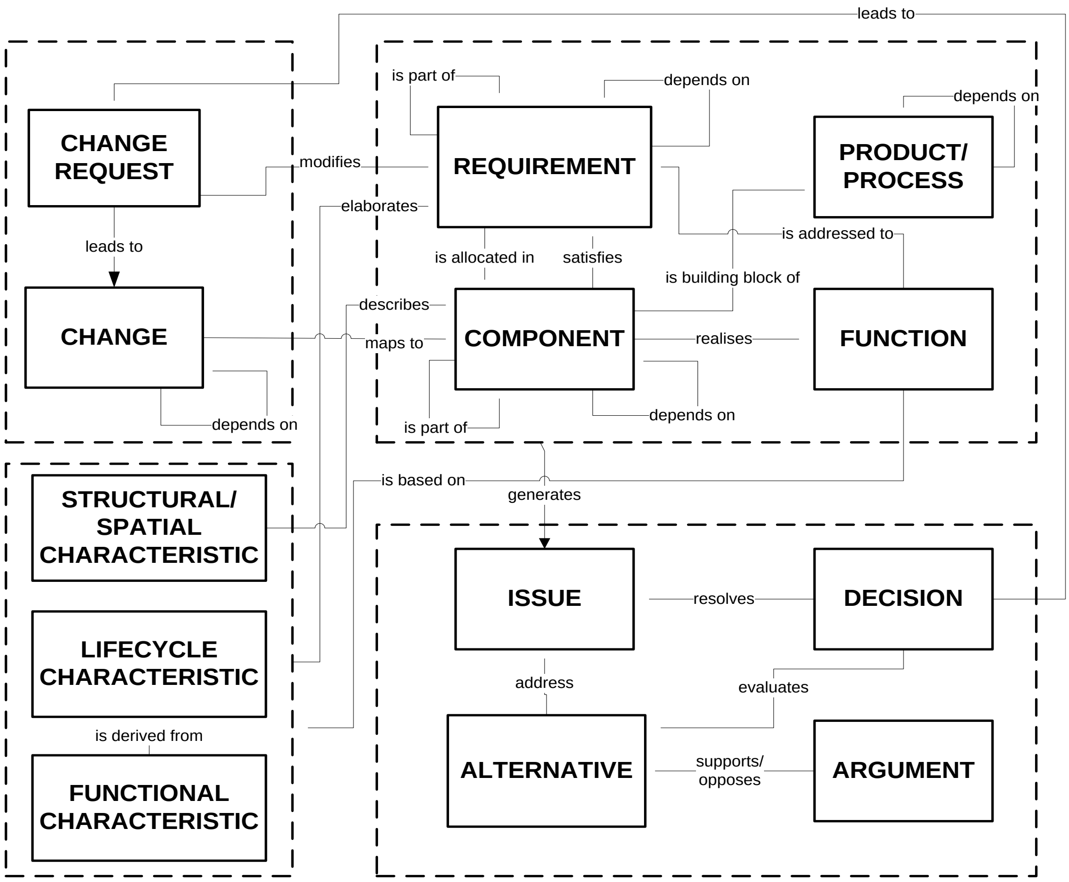

Figure 3. Product related elements of the reference model (partial view)

When product developers need to process requirement, they typically need to understand the background of the requirement, the origin of the requirement, and how requirement is addressed in the developed product through specific product characteristics. Traceability of the key product characteristics is crucial for evaluation and verification of the product development results and could help by explaining how characteristic affect a product's safety or compliance with governmental standards or regulations, or is likely to significantly affect customer satisfaction with a product. In order to process change request, designers need to understand the ramification of the request in the terms of the number of different product aspects like components or functions that would be affected and details about past decisions that may be relevant for the change request. Design rationale including issues, arguments, alternatives and decision is also required at a fine-grained level to provide product developers a clear understanding of design decisions made. Alternatives suggest different solutions to issues, each of which can have supporting and opposing arguments. Decisions are usually made by evaluating alternatives.

Presented model partially illustrates product related traceability elements as addition to the process related traceability elements, thereby providing a structure for traceability of the information development in product development support at a fine level of understanding granularity.

5.2 Preliminary evaluation

At the beginning of the product development project when traceability episode planning is ongoing, the templates of the traceability records that will be used in particular episode are defined. The traceability elements, links including their semantic, and traceability execution properties like events and project points that should drive traceability during product development are selected accordingly to the reference model. As a case study for evaluation of the proposed methodology two product development projects from two different industrial partners have been selected. One of this was development of the software and hardware components for central controlling unit of railway vehicles and another is development of the new generation of a mechatronic car seats.

Since the implementation of TRENIN framework in PLM environment [6] is ongoing, we used OntoStudio© by Ontoprise GmbH (www.ontoprise.de) as a collaborative ontology engineering

environment for TRENIN ontology and traceability records development. Based on the interviews with the members of the product development departments, the basic TRENIN ontology was extended in the reference model for each company. Reference models have been created to contain the company specific instances of the ontology concepts with the specific focus on requirements and characteristic perspective important for testing procedures. Product related traceability elements have been defined by instantiation of the requirement-, function-, component- and characteristic taxonomies for each development project. Process related traceability elements have been defined by instantiation of the activity taxonomy with the goal to trace key events during the development process and understand how information objects related to the requirements and product characteristics have been developed.
Since OntoStudio© is framework for engineering, the traceability execution was simulated by the researcher following the real development process. During the each project meeting at all levels, researchers have been recording the situation by mapping information objects to the elements of the reference model and capturing in such way the current state for the further analysis. The result of the evaluation procedure was set of the different recorded states of the traceability records based on the chosen template, semantically connecting and explaining how different information objects like documents, parts, web sites, telephone calls, etc are interrelated semantically and how the informational content that they are containing has evolved during the product development episode. Because of the semantically enriched reference model, information objects become more accessible, the extended filtering and search procedures based on the ontology elements were used in order to understand recorded context o information development, and context relevant utilization of the information objects by means of tracing and explaining information development evolution become possible.
Preliminary results of utilization have shown that more efficient and context sensitive process of information reuse has been established by using traceability records, confirming that proposed traceability methodology could be actively used in engineering practice. Of course, questions of usefulness versus investment of the resources for tracing should be further considered during implementation and integration of the traceability records in daily engineering environment as one of the key functional specification.

6 CONCLUSION

The presented research makes the following contributions to the TRENIN (www.trenin.org) project:

- Presents traceability reference model that integrates four perspectives on traceability pointed out by industrial partners and research literature.
- Presents an approach for managing product and process information support by integrating different information objects.
- Presents an approach to trace product and development process information on the fine-grained level.
- Illustrates traceability management approach based on the ontology that could be generalised to other disciplines.

The three tier implementation architecture of the TRENIN framework in PLM tools environment will be presented in the further publications [6]. It is expected that the implementation of the traceability reference models and methods in PLM environment will enable semantic and structural guidance to full engineering information objects integration and efficient utilisation of the engineering information fragments during product life cycle.

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Contact: Mario Štorga, Ph.D.
University of Zagreb, Faculty of Mechanical Engineering and Naval Architecture
Ivana Lučića 5, Zagreb, Croatia
Tel: +385 1 6168 432, Fax +385 1 6168 286
Email: mario.storga@fsb.hr, URL: www.cadlab.fsb.hr

Mario is Assistant Professor in the Department of Design at the University of Zagreb Faculty of Mechanical Engineering and Naval Architecture. He teaches and researches in engineering design and product development. He is interested in knowledge and information management in engineering design, product and process formal modeling and product life cycle issues.