Development and Implementation of an Ontology to Support the Product Development of Smart Textiles Using Open Innovation Platforms

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***Abstract*—To create innovative connected products and services, more and more interdisciplinary development efforts across industries covering hardware, software and business model design are required. One example for this is smart textiles, where the complexity of the value chain has so far hindered the successful market launch of new products. In this paper, semantic web ontologies are used to support faster development and market entry by a structured interaction of all players along the value chain. A specific *Smart Textiles Ontology* is defined, validated and evaluated with the help of the structured incorporation of expert knowledge. The ontology acts as a foundation for an open co-innovation platform called GeniusTex, and has successfully enabled first product development projects.**

Keywords–Ontology Development; Smart Textiles.

I. Introduction

Smart Textiles are textiles with an extended range of functions that enable the interaction of the textile with the environment and the human user. Applications range from shirts for monitoring vital signs, activity or stress in health and sports to displays integrated in furniture and protective and heating equipment in industrial settings [1]. A standard of the European Committee for Standardization (CEN) defines *Smart Textiles* more specifically as intelligent systems consisting of textile and non-textile components that actively interact with their environment, a user or an object. Data is recorded and processed via sensors and a defined reaction is generated via actuators or an information display on a supplementary device [2].

The market outlook for smart textiles is very promising, with a market size of approximately €5 billion for 2022, growing from €1.3 billion in 2017 [3]. However, this potential has not yet been realized and few products have passed from prototype stage to mass market. Challenges arise mainly due to the complex value chain of smart textiles that includes textile and electronics suppliers, software and application developers, product designers and manufacturers (system integrators), as described also by [1], [4]–[6]. Such challenges are:

- *Technical challenges* that include the complex design of interfaces between textile and electronics components, the miniaturisation of all components for the seamless integration in textiles, as well as their usability and durability. To solve these challenges, expertise from different knowledge domains, such as textiles and electronics production, needs to be combined during the Product Development Process (PDP).
- *Organizational challenges* that emerge from diverse value chain which has limited experience in collaboration across the different knowledge domains. Due to a lack of standards in the smart textiles domain, the producers cannot refer to norms to ensure interoperability between their domains, but need to collaborate intensely with all parties along the value chain during the PDP.

This paper describes how the GeniusTex project addresses these complex challenges by utilising a *Smart Textiles Ontology*, which can be retrieved from [7], together with a co-innovation platform.

- Related work on ontologies for collaborative product development and (smart) textiles (Section II)
- Defining an Ontology as common language to describe the modules and diverse knowledge areas of smart textile domain (Section III)
- Validation (Section IV) and implementation on a co-innovation platform called GeniusTex (Section V)

II. Related Work

Product and process development needs to handle a demand for shortened and more efficient development cycles despite higher product complexity [8]. Modularization is an established method to handle the complexity of product development and production processes by dividing the product into modules with clearly defined interfaces and relationships. This structured representation of the product enables both parallel development of modules, as well as reusing previously developed modules in new products [9]. Plus, a modular product concept simplifies collaborative development projects that involve different players along the value chain. While this has been the standard approach for collaborating both in development and production for industries like automotive, where Original Equipment Manufacturers (OEMs) and suppliers are highly integrated, it has not been adopted yet in the textiles domain [10]. Small and Medium Enterprises (SMEs) lack the integrated supply chain, especially to cover both textile, electronics and software components required for smart textiles.

Knowledge management and information sharing across all parties involved has been identified as a crucial prerequisite for successful development processes [11] [12]. Ontologies are one concept to support this by acting as a ”common language” between modules and parties involved in PDP. An ontology has been defined by Gruber [13] as a formal, explicit specification of a shared conceptualisation. Ontologies support knowledge management by structuring knowledge domains into classes with properties and relations, thus allowing for searches and processes to be defined along the structures [10]. Since ontologies can be expanded, adapted and merged, they can support knowledge domains subject to changes in technological advances [14].

A. Ontologies enabling collaboration along the value chain

The use of ontologies to support the PDP has been described in literature for various knowledge domains, for instance to promote knowledge integration and sharing [12]. In addition to the mere provision of knowledge, ontologies can also enable decision-support in the PDP, e. g. by automatically finding previously developed modules or documents with high similarity to the current product specification [15], or suggesting new combinations of prior modules into new products [16]. Moreover, ontologies have been applied with a focus on collaboration and co-innovation. The collaborative product innovation network by Song et al. applies ontology based knowledge integration to reduce the development time of a water heater [17]. To integrate knowledge across different players along an aviation development process, Li et al. merge and map local ontologies into a global ontology for knowledge sharing [18].

B. Ontologies for Textiles

For textiles, there are few examples of structured knowledge management using ontologies. A knowledge exchange infrastructure has been proposed to promote collaboration [19] and to support interoperability in the textile industry [10]. The *Textile chemical ontology* focusses on hazardous and forbidden chemicals for textiles, e. g. by formalizing standards like the OEKO-TEX label [20]. While the *VetiVoc* ontology addresses only the fashion domain rather than technical or smart textiles, it gives an example how textiles can be modularized [21].

C. Ontologies for Smart Textiles and Services

In the domain of smart textiles and services, ontologies have been applied mainly for integrating different data sources. For example, sensor data collected by a wearable are combined with historical health data and weather data for health care services [22] or used to process wearable sensor data into specific human gestures [23]. The ontology-driven open reference architecture and platform around services for elderly of the project *OASIS* combines multiple measurements from smart textiles for unobtrusive monitoring applications [24].

However, the idea of exploiting modularity to handle the complexity of smart textile development processes has been introduced for example by Schwarz et al. [25]. They describe 6 functions of an intelligent textile system whose interdependence needs to be accounted for during the PDP, and which act as foundation for the functional components of a smart textile introduced in Section III. Similarly, reusing certain modules for multiple products is promising to reduce time and costs of smart textiles development. The *Simple Skin project* proposes textile building blocks where a conductive fabric acts as foundation for various products and services [26]. The *EASY-IMP project* described the use of meta-products that can be enhanced with different modules and services [27].

This research aims at exploiting the potential of ontologies to support the PDP of smart textiles. To address their specific challenges and the gaps in previous research, the Smart Textiles Ontology focuses on two objectives:

1) structured and accessible knowledge base across the smart textile domain
2) enabler of collaborative development and co-innovation processes

III. Defining the Smart Textiles Ontology

The domain of smart textiles covers multiple areas, such as textile materials, electronic components, as well as manifold steps of the production process. Hence, an ontology for smart textiles should cover these concepts and allow to express interdependencies among them in order to direct development projects. The scope of the ontology is determined by a set of natural language competency questions that are expected to be answered by the ontology in the end.

The smart textiles domain is described in modular structure, looking at classes of processes, materials, and component modules. Component modules include the functional parts that make a textile smart (sensors, actuators), data processing, data transmission and interconnection modules, as well as textile carrier or substrate. The production processes cover joining, separating, forming, handling and quality control. The focus lies on the joining class, as it includes the critical processes of integrating functional components to a textile carrier and the contacting between different components. For all these modules, properties and relations that describe the interdependencies between materials, components and processes are defined. This allows for the codification of domain knowledge specific to smart textiles: e. g., the drapability and elasticity of components is a critical property. While it is common to account for this in textile processing, for developers with an electronics background it is crucial to know this to select both electronic components and technologies for handling and integrating them accordingly.

A common challenge for any ontology development project is the effective involvement of domain experts. Specialists in related fields possess knowledge and skills that are indispensable for the construction of a domain ontology. Whereas they neither have to be experts in ontology development nor in the rather technical tools, the contributing knowledge engineers are often no experts in the domain. To overcome this problem in the GeniusTex project, the domain experts are provided with a minimal knowledge acquisition template, which is familiar to them. In this particular case, we use an Excel master document for collecting the ontology elements. There, the domain experts simply have to fill in labels, definitions, and straightforward references (e. g., superclass, domain, and range) for *Classes*, *Relations*, *Attributes*, and *Individuals*. This still demands a fundamental understanding of what an ontology is, but keeps away the technicalities of developing an OWL ontology.

The actual ontology is automatically built by the *eccenca Ontology Pipeline* based on the master document and the configurations made by a supporting knowledge engineer. The domain experts get immediate feedback in form of a validation report and an ontology visualisation (c. f. Section IV). The eccenca ontology pipeline is integrated in a continuous integration pipeline, which regenerates all relevant artifacts on updating the master document. With each commit the pipeline (1) generates an OWL file, (2) validates the ontology file resulting in a validation report, (3) creates a corresponding visualisation and (4) an ontology documentation. The WIDOCO tool [28] is used in this setting. These artifacts are immediately accessible to the editors (domain experts and knowledge engineer), i. e., with each commit the contributors get information whether the ontology was build successfully and could be validated, as well as a visual representation.

According to the elements defined by the domain experts, a knowledge engineer solves particular ontological problems and enforces best practices, e. g. mapping of external ontologies, realising consistent structures and naming conventions. He also defines example instance data which is used to validate the ontology.

The GeniusTex Smart Textiles Ontology reuses concepts from multiple external ontologies, such as

- the *Semantic Sensor Network Ontology* (SSN) for the description of sensor features [29],
- the *Ontology of Units of Measure 2.0* for representing units of measurement needed to describe sensor features [30], whereas a number of very specific units had to be replenished for the textile domain, as well as
- *schema.org* for general product aspects of individual components, e. g. dimensions and price.

IV. Validation and Evaluation of the Smart Textiles Ontology

To ensure an adequate level of quality throughout the ontology development process, routines have been set up to check for multiple validation constraints after each development step. Finally, the Smart Textiles Ontology has been evaluated with actual data.

A. Validation

During the ontology development, it is crucial to validate the ontology after each development step in an automated way in order to find problems and quality issues fast. There are several criteria to validate an ontology. Some of these criteria can be checked fully automatically, such as syntactical correctness, logical consistency, and the application of some best practices. Other criteria demand judgement from experts who have a certain domain knowledge. For example whether the ontology is coherent to a common understanding of the domain.

We are following this approach with a continuous integration ontology development pipeline, which generates reports on each revision of the ontology. The aim is to evaluate and report as many things a possible in an automated way. These reports are played back to the domain experts who are obliged to keep the ontology in a validated state with every change. The *eccenca Ontology Pipeline* is based on a version control system and a continuous-integration (CI) server. The build process and integration tests are run automatically on the CI server when a new commit has been made:

1) The build process compiles the ontology from a knowledge acquisition template and several configurable source files.
2) An RDF parser (in this case, Apache Jena RIOT) ensures syntactical correctness.
3) An OWL reasoner (in this case, Pellet [31]) ensures logical consistency.

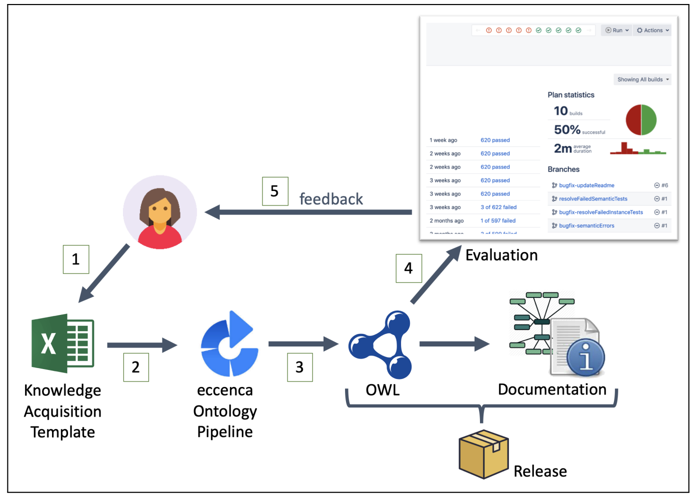

Figure 1: Continuous Integration Workflow.

4) RDFUnit [32] ensures a number of general best practice requirements, which are defined as tests in form of SPARQL queries or SHACL shapes.
5) OWL2DOT generates a visual representation of the ontology elements (see Figure 2).
6) WIDOCO generates an ontology documentation HTML document explaining the ontology elements.

The overall workflow is depicted in Figure 1. The results of all tests are collected as build artefacts on the CI server and respective authors (committers) are automatically informed if one of the tests fails. Furthermore, the generated documentation allows domain experts to inspect the defined elements in order to spot problems and share the current state of the ontology with colleagues. RDFUnit generates tests from the involved ontologies and executes these tests on the ontology definition and the optionally given instance data. The best practice requirements that are currently configured are mainly targeting documentation aspects, whereas it is desirable to extend these in the future:

- All defined resources should have an rdf:type
- All defined resources should have at least one label and a comment
- All defined resources should have different comments in different languages
- All defined resources should have a label different from its comment
- All labels and comments must not contain *todo*, *foo*, *bar*, *lorem* or *ipsum*
- Two defined resources should not have the same comment
- Two defined resources should not have the same label
- All resources defined by an ontology should be prefixed with the ontology URI and link this ontology with rdfs:isDefinedBy
- All ontologies should state their preferred namespace prefix
- All ontologies should state their preferred namespace matching their URI

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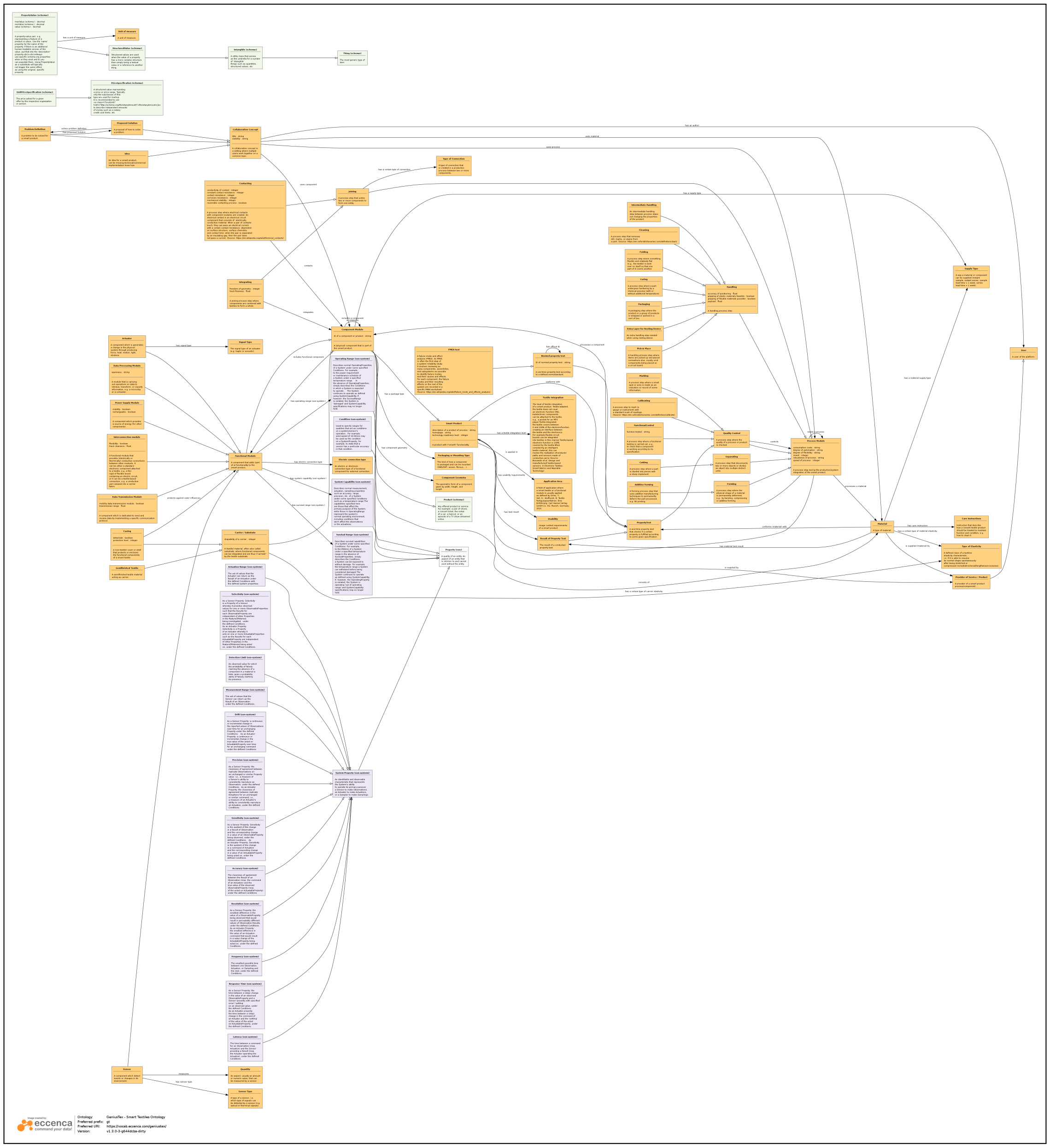

Figure 2: A visual representation of the Smart Textiles Ontology.

- All ontologies should have a version info

By adhering to these concepts, it can be made sure that the ontology remains valid and operational during its development cycle. Secondly, it leads to a more consistent development in general and an overall quality improvement.

B. Evaluation

In order to evaluate the Smart Textiles Ontology, a graph had to be populated with respective A-Box data. This has been done based on actual data on smart textile components along two example products (smart orthosis, smart wristband) as it occurred in the project. The data has been transformed to RDF using eccenca's Corporate Memory data integration capabilities. While doing so, the resulting triples have been continuously validated against the ontology.

For evaluating the ontology, 27 (out of originally 35) competency questions have been translated to SPARQL queries and finally executed on our knowledge graph. The questions have been collected at the beginning of the project, so that eight questions were not covered by the ontology in the end, mainly due to data gaps (e. g., *CQ 3.4 Which companies can create a prototype with SMD (surface mounted device)?*) or an no further pursued meta-level (e. g., *CQ 3.7 What is generally required for approval of a smart textile?*).

An example query for *CQ 2.11 Which actuators, which emit light or acoustic signals, are smaller than 20x20x3mm?* can be seen in Listing 1, it filters actuators by their signal type and physical dimensions. Since for all dimensions the millimetre unit is used, it has been neglected here (c. f. Section VI-A).

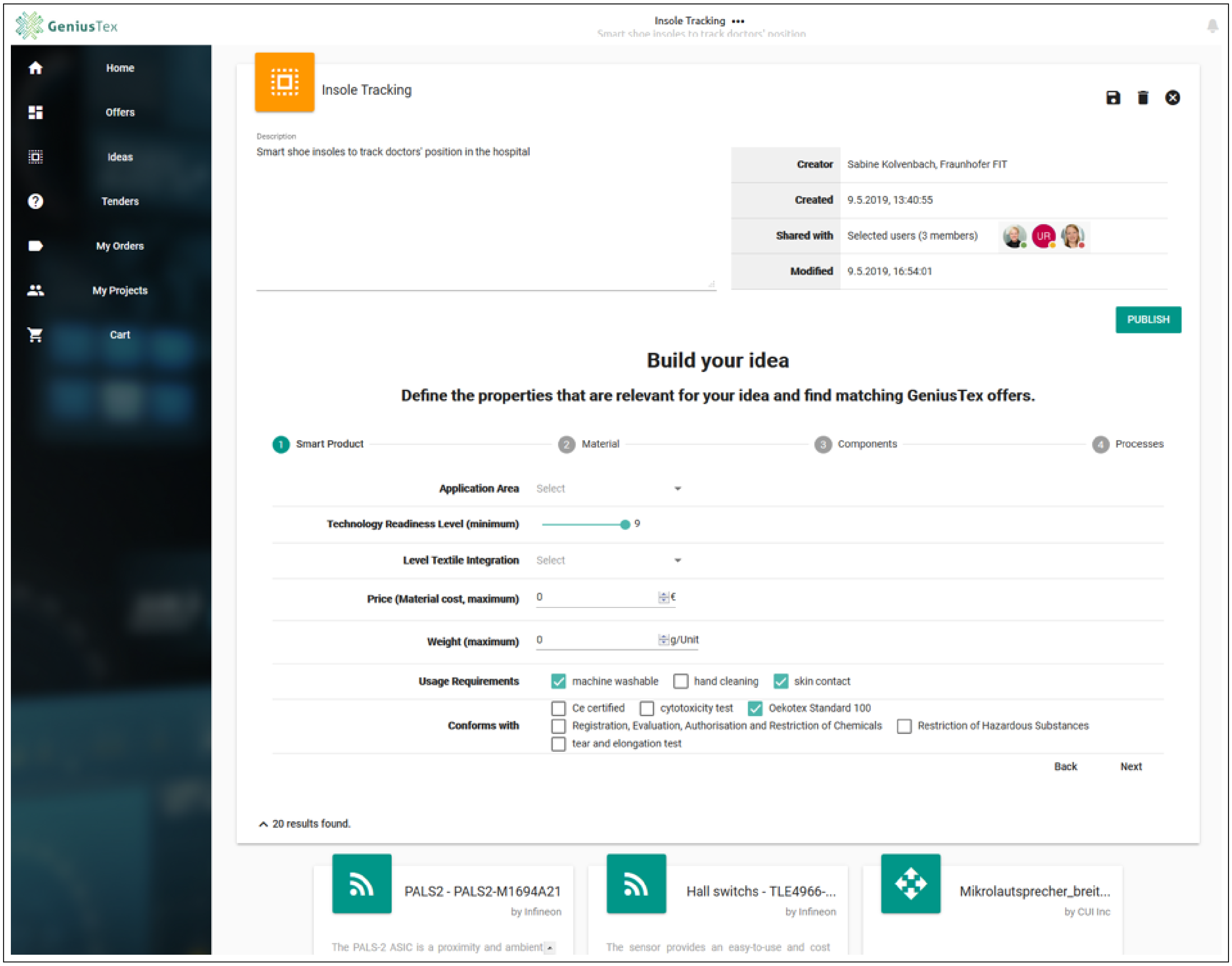

Figure 3: The collaborative GeniusTex Idea Configurator.

Listing 1: Query

```
<SELECT * WHERE {
  ?act a gt:Actuator ;
    gt:hasSignalType ?signal ;
    schema:depth [schema:value ?d] ;
    schema:width [schema:value ?w] ;
    schema:height [schema:value ?h] .
  FILTER (?signal = gt:opticsignal ||
          ?signal = gt:acusticsignal)
  FILTER (?d <= 20 && ?w <= 20 && ?h <= 3)
}
```

V. Implementation on GeniusTex - Current Infrastructure

Beyond the modularization of smart textile products, services and processes with the Smart Textiles Ontology, GeniusTex addresses the challenges of the smart textiles PDP with an open innovation platform. The platform enhances the PDP along the smart textile value chain by enabling all involved stakeholders such as manufacturers, suppliers, service-providers, and end-users to connect, collaborate, ideate, and develop innovate business models. Main features of the GeniusTex platform are the import of ontology-based product data and its semantic representation, intelligent search to find and order relevant and compatible smart textile products, ideas browsing and collaborative idea configuration as well as information sharing in protected workspaces to generate new knowledge with experts and end-users.

Figure 3 shows the shared idea "Insole Tracking". The three idea members can collaboratively build the idea by defining the properties that are relevant for the perspective smart textile product. In this example, authors are interested in smart products with the *TRL 9* (highest level of technology readiness), which have to be machine washable, are designed for skin-contact, and conforms to *Oekotex Standard 100*. GeniusTex finds twenty results that match the configuration. Idea members can browse the results, find detailed product information and order suitable products. Moreover, users can

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publish the idea to the GeniusTex community with intend to find and discuss with other experts. GeniusTex platform users get notified of the published idea and can ask for joining the PDP.

VI. CONCLUSION AND FUTURE WORK

The application of an ontology has been proven as an eligible common language in the multi-disciplinary field of smart textile development. The steep learning curve that comes along the ”ontological overhead” faced by many domain experts confronted with an ontology development project, could be obviated by providing them familiar tools and immediate feedback mechanisms. Nevertheless, some decisions have to be made by knowledge engineers who are aware of the technological pitfalls.

A. Learnings: success factors for applying the Smart Textiles Ontology

When creating the Smart Textiles Ontology, a number of existing concepts from external ontologies have been reused, which is in particular helpful for compatibility reasons. Nevertheless, we experienced some issues which are generally unresolved: There are plenty of ways, but no standard pattern to represent measurements and physical quantities in RDF, i. e. values with well-defined units. We decided to go for schema.org's `PropertyValue` pattern, mainly because it supports values and value ranges along with units of measurements, for which the Ontology of units of Measure (OM) is used. While this approach allows to explicitly express values, it became apparent that it is on the other hand intricate to write queries for that model. Furthermore, it would actually be necessary to convert units of measurement during the query process to compare between measurements using different units, e. g. as suggested by Lefrancois using Custom Datatypes [33]. To really benefit from this variety of representation possibilities it would be beneficial to have the ability to transform between standard representations. Likewise, even though multiple ontologies for units of measurement exist, none is fully covering units from all domains [34]. Consequently, a number of units for the textile domain were added to the OM ontology.

B. Outlook: Internationalising and broadening the functionalities of GeniusTex

The Smart Textiles Ontology and its implementation on the GeniusTex platform help to streamline smart textile product and process development. So far, it has enabled three co-innovative development projects across different application areas: a smart orthosis, a smart wristband, and a connected pillow. To better support future projects, further functionalities have been identified, such as the link to broader product databases, modelling of complex inter-dependencies and rules within the ontology and improving search and recommendation functions based on this. Moreover, the internationalisation of the ontology and the platform is a next step. To ensure both platform architecture and its structured language are globally accessible, workshops with partners from different linguistic backgrounds, e. g. from South Korea, are conducted.

Finally, the platform-based development approach enabled by an ontology is applicable beyond the smart textiles domain. It is relevant whenever interdisciplinary domain knowledge from suppliers, manufacturers and service providers from different industries needs to be combined to create innovative connected products and services.

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