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Developing an Ontology for User and Customer Scenarios to Support Model-Based Cross-Generational Modelling of Products and Production Systems in Circular Economy

Kristian Vlajic[a,*], Yutong Tang[a], Julian Hannes Dreher[a], Stefan Eric Schwarz[a], Gabriel Moser[a], Tobias Düser[a], Albert Albers[a]

[a]*IPEK – Institute of Product Engineering, Karlsruhe Institute of Technology (KIT), Kaiserstr. 10, 76131 Karlsruhe, Germany*

* Corresponding author. Tel.: +49 721 608 47306. E-mail address: kristian.vlajic@kit.edu

Abstract

Modern product development faces the challenge of developing value creation strategies that are both environmentally sustainable and economically viable. The circular economy provides a promising approach by decoupling resource consumption from economic growth through regenerative product life cycles that potentially maximize value retention. Model-Based Systems Engineering provides a formal, adaptable approach to managing this complexity by enabling holistic, interdisciplinary representations over the entire product lifecycle. To support model-based cross-generational modelling of circular products and production systems, a dedicated ontology is essential. Yet, within the power tools domain, there is still no systematic definition of user and customer scenarios to derive requirements for product and production system development. This work addresses this gap by adapting ontologies from different domains, such as autonomous driving, to model user and customer scenarios in the power tools domain, using angle grinders as a use case. Additionally, literature analysis, interviews, and surveys were conducted to identify a possible definition of user and customer scenarios and cluster elements for the ontology. Future work focuses on automating the generation of scenarios for requirement identification and the integration of the ontologies into the system model for the perpetual innovative product, creating a framework that supports model-based execution.

Keywords: Scenario Planning; Applied Ontology; Product Development; Model-Based Systems Engineering; Circular Economy

1. Introduction

Modern product development faces the challenge of developing value creation strategies that are both environmentally sustainable and economically viable [1]. One promising approach is the circular economy, which aims to decouple economic growth from resource consumption by promoting industrial systems designed to be restorative and regenerative [3]. Unlike the traditional linear model, the end of a product's life is treated as the beginning of a new cycle [3]. Within the circular economy, remanufacturing is a key strategy, offering products of equal quality to new ones [4]. Despite its potential to save resources, reduce energy use, and lower CO_2 emissions, remanufacturing adoption remains low [5]. In 2021, remanufactured products made up only about 5% of relevant sectors in the EU, except for aviation, where the share was around 10% [6]. This shows that circular economy principles, particularly remanufacturing, are still in an early phase of implementation [5].

For the strategic planning of circular products and their related production systems, current and future user and customer requirements must be considered across product

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generations [7]. This involves identifying a broad spectrum of possible scenarios to determine the requirements for product and production system development.

At the same time, products are becoming more complex due to the increasing number of functions, subsystems, and interactions in modern designs [1,9]. Model-Based Systems Engineering addresses this challenge by using a central system model of the product that offers a formal, adaptable approach to manage this complexity by enabling holistic, interdisciplinary representations over the entire product lifecycle [9].

To define suitable requirements for future product generations and their production systems, an ontology is needed that attempts to map user and customer scenarios consistently and holistically for a system model for circular products.

To address this gap, the present work examines the understanding of user and customer scenarios. The terms user and customer scenario are described with a literature analysis. An empirical study clusters typical elements that emerge for user and customer scenarios using the example of an angle grinder. This allows an ontology for user and customer scenarios to be developed based on references to scenario modelling from different domains, like autonomous driving.

2. State of the art

The term *"scenario"* includes diverse meanings and is used to describe structured, consistent, and plausible representations of possible future states, serving primarily in anticipation and strategic planning [10,11]. Scenarios reduce complexity by integrating interconnected influencing factors and provide a flexible framework for reflection and decision-making. Central principles include open-ended, systemic thinking, with scenarios functioning as tools to depict conceivable and uncertain futures [11,12]. Their division includes, for example, environmental scenarios, emphasizing external uncontrollable factors, and action scenarios, focused on changeable development paths [14,11]. Levels of analysis include micro (products, users), meso (organizations, industries), and macro (societal) scales, which are functionally interrelated [15]. The consideration of users and customers, therefore, operates at the micro level of scenario description.

The roles of customers and users need to be differentiated within scenarios. Customers act primarily as economic decision-makers in procurement, while users engage with products operationally, emphasizing functional and ergonomic requirements [16,17]. This distinction is crucial for accurately capturing diverse stakeholder perspectives and requirements within scenario-based analyses.

The relationship between users, customers, and scenarios can be effectively modeled using ontologies, which provide a structured representation of interconnected entities and their interactions. Gruber [18] states that ontologies provide a formal and structured means of representing domain knowledge by defining classes, properties, individuals, and their relations [19]. This enables consistent representation, automated reasoning, and inference of implicit knowledge, supporting applications such as semantic analysis and simulation [20]. In this context, it makes sense to build the ontology for users and customer scenarios on references.

The High Quality Data Models (HQDM), introduced by West [21], defines fundamental categories of entities and relations within a metamodel. It aims to overcome common shortcomings of traditional data models, such as semantic ambiguity, inconsistent categorization, and limited extensibility. By providing a rigorous ontological foundation, HQDM ensures that data models represent real-world phenomena in a consistent, precise, and logically coherent manner.

The Context Awareness Meta Ontology (CAMeOnto), introduced by Aguilar et al. [22], is designed as a domain-independent meta-ontology that can be specialized for concrete applications through a set of core classes and relations. Its structure organizes scenarios around users, devices, services, activities, roles, locations, environments, and time, all formally connected via object properties to support reasoning and interoperability.

ASAM [2,8] has developed complementary standards to OpenXOntology that enhance the description and simulation of domain-specific scenarios, notably OpenODD and OpenSCENARIO. OpenODD provides a machine-readable framework for formally describing the Operational Design Domain of automated systems, focusing on environmental and contextual conditions such as weather, road type, and infrastructure. Represented typically in JSON or YAML, it supports interoperability, systematic testing, and validation by defining the operational boundaries of a system. In contrast, OpenSCENARIO specializes in modeling dynamic activities, interactions, and temporal sequences between actors, enabling the specification and simulation of maneuvers and conditional triggers in traffic domains.

For user and customer scenarios, HQDM provides a robust ontological foundation that addresses ambiguity and extensibility limitations of traditional data models. This provides a structured and formally grounded methodology for developing data and ontology models in engineering and related disciplines. CAMeOnto offers a generic framework for modeling context in pervasive and intelligent systems, encompassing key dimensions such as users, devices, activities, roles, locations and time. Although CAMeOnto serves as a strong conceptual basis, it requires adaptation for engineering-specific disciplines like product development. Similarly, ASAM OpenXOntology, originally developed for automated driving, presents structured modeling principles with significant potential for user and customer scenarios. However, OpenSCENARIO's activity modeling remains traffic-specific, restricting its direct applicability to domains such as power tools where activities and interactions differ substantially.

3. Research approach

For the research gap the reviewed literature suggests that there is no consistent understanding of user and customer scenarios. The ontologies examined show that while the proposed ontology frameworks are promising, there is no adequate ontology for user and customer scenarios in the power tools domain. From this, it can be concluded that the research objective is to formulate a general understanding of user and customer scenarios for this work and to develop an ontology-based scenario model that systematically supports the generation of user and customer scenarios and the associated derivation of product requirements. The model was developed based on the example of an angle grinder to capture market expectations and the operational area to support the product and production system development of the circular product [23]. The example is a sufficiently complex mechatronic product with an easily understandable composition [23]. This results in the following research questions.

RQ1: What understanding of user and customer scenarios can be derived from existing approaches to improve the derivation of product requirements?

RQ2: Which elements can be identified and clustered for user and customer scenarios using surveys and interviews based on the example of an angle grinder?

RQ3: How can an initial ontology model be constructed to formally represent user and customer scenarios, using different ontology references and the angle grinder as a case study?

The research approach is structured according to [10]. To answer **RQ1**, a literature analysis was conducted, focusing on scenario modeling and user and customer descriptions. For **RQ2**, based on the findings from **RQ1**, surveys and interviews were carried out to identify a cluster of relevant elements for the user and customer scenario description. Finally, in **RQ3**, ontologies with entities and their relations are constructed in the scope of power tool usage with references from the scenario modeling of autonomous driving and the findings from **RQ2**.

4. Results

4.1. User and customer scenarios

Users and customers represent complementary approaches within product development. Customer scenarios primarily address procurement processes, decision-making logic, and economic considerations, while user scenarios depict specific usage situations, working environments, and ergonomic conditions [16,17]. Kosow et al. [15] suggest that user and customer scenarios are considered micro-scenarios, as they focus on products, processes, and user groups.

The scenarios can be designed to be both exploratory and anticipatory [13]. In product development, customers provide insights into political, regulatory, and economic conditions, while users assess suitability for everyday use [16,17]. An understanding of this work for user and customer scenarios is therefore as follows:

A *user scenario* describes a specific and detailed usage situation in which a user operationally uses a product or service. It highlights the relevant influencing factors, requirements, environmental conditions, and usage context and is used for the user-centered development and validation of products.

A *customer scenario* describes a specific situation in which a customer interacts with a product or service and highlights the conditions and requirements of the procurement process. It provides a systematic understanding of the interaction between the customer, product, and environment and is used to develop, adapt, or evaluate products, business models and services.

4.2. Empirical study

For the empirical study [24], 19 people were interviewed in 12 interviews (eight individual and four group interviews). 15 respondents were from the skilled trades (carpenter, industrial mechanic, precision mechanic, mechanical technician, industrial clerk), supplemented by two from power tools research and two from the emergency services. The focus on the skilled trades results from the high practical relevance of angle grinders. A differentiated selection was made within the sectors to reflect a variety of perspectives. In addition, to provide a perspective that was not professional but close to everyday use, 30 individuals from different research backgrounds took part in an online survey. On this basis, essential descriptive aspects for scenario construction could be derived. The data from the interviews and the survey can also be found in the evaluation of the empirical study [24].

The activity of angle grinders is mainly cutting and grinding, supplemented by polishing, deburring, and paint removal. A wide range of materials are processed, including metal, wood, stone, concrete, plastic, and coated surfaces; typical workpieces are bar materials, structural elements, and components. The use is divided into preparation (personal protective equipment, workpiece fixation, disc selection), execution (cutting technique, body posture), and follow-up (cleaning, maintenance). In terms of devices, corded and battery-powered devices dominate, with battery-powered devices offering mobility and mains-powered devices offering performance advantages. Robustness, system compatibility, and good handling are crucial. High-quality grinding discs and special attachments are essential accessories. Premium manufacturers are preferred. Operating conditions such as confined spaces, restricted sightlines, or workpieces that are difficult to access pose particular challenges. Safety aspects are essential and protective equipment, reliable workpiece fixation, and disc control are considered mandatory. Risks arise from flying sparks, disc breakage, jamming, heat, dust, and noise. Ergonomic requirements relate to weight, geometry, vibration protection, and transport solutions. Cordless tools offer advantages for longer periods of use. Maintenance practice includes cleaning, cable care, disc inspection, and safe storage.

The online survey reveals parallels between private and professional use of angle grinders. The main applications are cutting and grinding, primarily of metal, wood, stone, and concrete. Safety aspects are highly relevant in both contexts, especially for younger and inexperienced users in the private sector. Differences mainly exist in the general conditions. DIY enthusiasts usually work with semi-professional equipment under improvised conditions, whereby serviceability is hardly an issue due to infrequent use. Functional factors such as type of application, material, machine specifications, and accessibility of the workplace remain decisive for use.

From the customer's perspective, the expert interviews show that procurement is context-sensitive, user-oriented, and system-dependent, with the aim of ensuring efficiency and quality of work. Decisions are made pragmatically, based on experience and the system, and tailored to existing machinery and manufacturer-specific battery systems. Key criteria include performance, durability, handling, ergonomics, safety, system compatibility, budget, and service. System loyalty and brand loyalty are based on battery compatibility, established product quality, and reliable service partners.

Table 1. Cluster of relevant elements for user and customer scenarios.

Category	User	Customer
Actor	• User profile • Occupational safety	• Customer profile • Safety aspects
Device	• Device equipment and accessories • Function and handling • Service and operational reliability	• Product specifications • Brand loyalty and preferences • Service and availability
Location	• Workplace and environment • Accessibility and freedom of movement • Potential hazards	• Operational structure and responsibility • Procurement structure and process • Regulations and standards
Activity	• Workpiece and material • Task • Complexity and processing context	• Procurement reason • Procurement objective • Functional needs

The survey results also show that private buyers have functional and safety-related requirements. Durability, performance, and safety features are particularly important. In contrast to the professional sector, which has a high premium loyalty, private users prefer robust devices from the mid-price segment; brand loyalty and battery system compatibility play a lesser role here. With the data obtained, the results of the empirical study were then analyzed to cluster the relevant elements for user and customer scenarios as shown in Table 1. The clusters are adopted from the CAMeOnto methodology, which provides structured guidance for representing scenario dimensions in engineering contexts, ensuring consistency and direct mappability to ontology elements [22].

4.3. Initial ontology for user scenarios

The ontologies are applied as formal representations of customer and user scenarios in the angle grinder domain, with knowledge represented as triples (subject–predicate–object) capturing entities and their relations. For example, *"user performs cutting task"* or *"cutting task involves power tools"*. This structure explicitly documents relations between users, activities, tools, and environments, enabling automated reasoning. In this work, only an excerpt of the proposed ontology model is shown, and a detailed description can be found in [25]. It builds on ASAM OpenXOntology and the High-Quality Data Model (HQDM) [2, 21]. A core principle of HQDM-based ontologies is reification. Aspects are modelled as entities rather than mere attributes. For instance, instead of "dust = high," a HighDustEnvironment entity is created and linked to the activity, allowing conditions to be represented more explicitly and extended with further relations. Following OpenXOntology, only one generic property, has value, is used for numerical data (e.g., spindle speed, torque). This entity-oriented approach enhances semantic clarity, supports reasoning, and ensures consistency across scenarios. The ontologies for users and customers are structured into two layers. A domain concept layer defining angle grinder–specific classes (User, Activity, Workpiece, Tool Component, Environment), and a core concept layer providing HQDM primitives (Object, Role, Event, State). Each domain class is systematically mapped to its HQDM-based core class, maintaining semantic consistency with established standards.

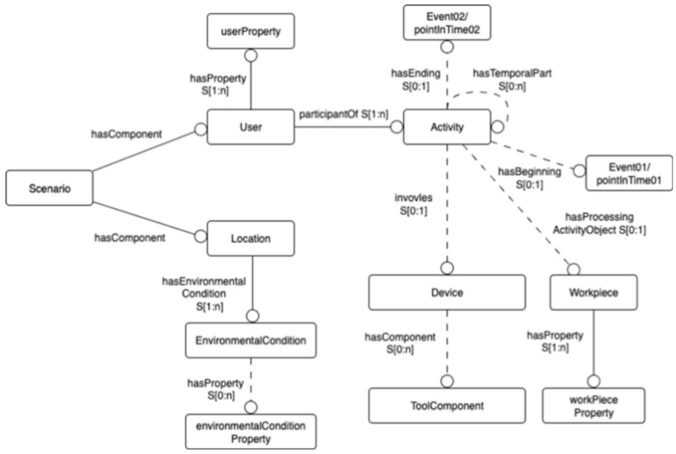

Fig. 1. Excerpt of the domain ontology structure for user scenarios [25].

In Figure 1, the user ontology describes how a user at a specific location performs an activity, which may involve tools, equipment, and workpieces. The location is defined by environmental conditions like lighting, dust, or flammable substances. Activities are time-structured, with defined start and end points, and can be ordered in sequence to show temporal relations. The dashed lines symbolize that a relation is optional or that it is not always necessary to record it. For example, not every environmental condition has a property, like FlammableCondition, which is a Boolean relation. The CAMeOnto core classes are selected because of their clear advantages in representing contextual relations between user, device, environment, location, time, and activity in a structured and reusable way.

Scenario: The scenario class models the socio-technical state of *"angle grinder in use"*, aggregating user, location, device, workpiece, and conditions. It maps to HQDM's system state, with cardinality constraints ensuring one operator at one workplace per scenario.

User: The user class represents the angle grinder operator within a scenario. It is modelled as a system component of the scenario and as a participant in activities, with constraints ensuring one operator per scenario and one activity at a time. The user is further described by user properties such as age, skill level, and occupational position, modelled as entities to allow richer semantics and reuse.

Location: The location class models the physical workplace where the angle grinder is used. Two categories are distinguished. Indoor (workshops, factories) with controlled conditions, and outdoor (construction sites, fieldwork) with variable conditions. Each location may have multiple environmental conditions, represented with cardinality [0:n] (e.g., lighting, dust, noise, temperature). environmental condition property classes define measurable or categorical aspects of each condition, with numerical values captured using the generic has value property.

Activity: The activity class is modelled as an activity state within HQDM and OpenXOntology, defined as a temporally bounded state with beginning and ending events. Activities are composed of participants and can be sequenced or decomposed into sub-activities, enabling representation of complex workflows. In this domain, activities are categorized into six types: operational, processing, execution, post-processing, preparation, and safety. Of these, processing activities are most significant as they directly reference the workpiece. This modelling approach supports precise representation of temporal order, hierarchical structure, and task dependencies in tool-use scenarios.

Workpiece: The workpiece class models the physical object processed by the device, represented in HQDM as both a system component and tangible entity. Its attributes are captured through the workpiece property, aligned with the physical property, covering geometry, dimensions, material type, hardness, and surface condition to support detailed characterization in machining scenarios.

Device: The device class models physical objects involved in activities, represented in HQDM as both tangible entities and system components. In the angle grinder domain, devices include the tool itself, clamping systems, extraction equipment and workbenches. Internal structures are captured through the tool component class, comprising control, drive, ergonomic, safety, and working attachments, enabling a structured representation of functionality and safety. Further sub-elements and instances are not considered further in this excerpt of the ontologies [25].

4.4. Initial ontology for customer scenarios

The customer scenario ontology models the decision-making process that occurs before tool use. It focuses on how customers evaluate and compare products, prioritize different properties, and are influenced by social or contextual factors.

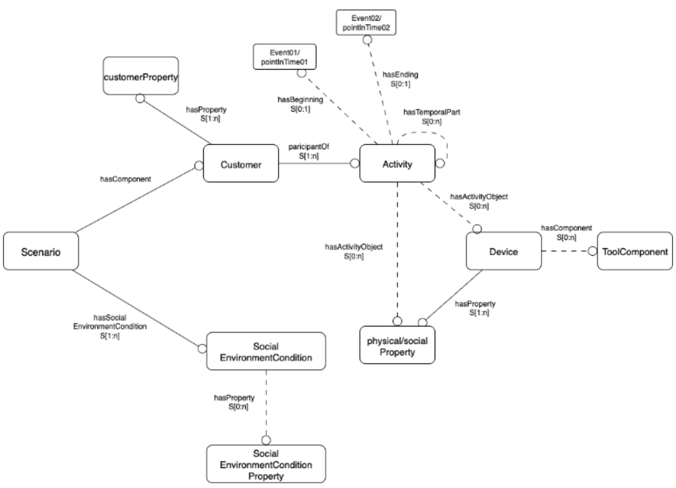

Fig. 2. Excerpt of the domain ontology structure for customer scenarios [25].

Figure 2 shows the central structure of this ontology. A scenario contains a customer and a social environment condition. The customer participates in decision-related activities, including considering various physical/social properties of the angle grinder and assigning higher priority to certain aspects when trade-offs occur. Unlike the user ontology, it was built inductively from empirical customer data rather than a reference model, while staying consistent with ASAM OpenXOntology and HQDM principles.

Customer: The Customer is modelled as a persistent system component, a participant in decision-related activities, and the bearer of customer properties. These properties cover both physical aspects (age, experience) and social aspects (brand trust, budget, organisation, position), providing a structured way to capture factors influencing purchasing behaviour and anchoring the scenario to the market perspective.

SocialEnvironmentCondition: The social environment conditions capture societal, regulatory, and economic factors influencing purchasing. They are classified into economic climate conditions with measurable indicators (e.g., GDP, PMI), legal regulations defined by compliance directives, and supplier relationships.

Physical/SocialProperty: Physical properties describe measurable technical characteristics such as energy use, ergonomics, mass, power rating, lifespan, and weight. Beyond measurable technical attributes, customer decision-making is also influenced by socially constructed aspects. The social properties include for example: system compatibility, leasing options, operating costs, operation needs and repair services.

5. Limitations

The results indicate that scenarios are a well-established method for structuring complex relations. However, independent definitions of user and customer scenarios seem underrepresented in the literature. To concretize the current understanding, extensive systematic literature research is necessary. Existing scenario research is predominantly focused on macro- and mesoeconomic perspectives, with actor-centered contexts being comparatively underexplored. The empirical study is, in its nature, limited by the sample size and varying levels of respondent experience and can always be improved. While the findings corroborate and enrich the scenario modelling, they require validation across disciplines.

The proposed ontology model offers significant strengths for user and customer scenario modelling, including extensibility through HQDM foundations, logical consistency enabled by an entity-oriented design, and strong machine-readability facilitating integration with digital tools. Its scenario-based structure demonstrates potential generalizability across various products beyond the angle grinder. However, challenges such as model complexity, data-intensive development, domain specificity, and limited real-world validation constrain its current applicability. In this context, to enhance robustness and usability, the empirical dataset can be expanded. These efforts will support advancing the ontology from a conceptual framework to a tool adaptable across the power tool domain.

6. Summary and outlook

Based on a literature analysis, a possible understanding of user and customer scenarios was developed. The results served as the basis for conducting interviews and surveys to form a cluster of relevant elements for the modeling of user and customer scenarios. Using reference ontologies, two initial scenario models were developed for customers and users.

The analysis of the current state of research shows that scenarios are an established tool for structuring complex relations, but that no consistent understanding of customer and user scenarios can be found in the literature. Their conceptual clarification was therefore carried out by synthesizing relevant literature on scenarios and the roles of customers and users.

A combination of qualitative expert interviews and a quantitative online survey was conducted. These provided practical insights and enabled the comparison and weighting of key elements. However, limitations exist in terms of sample size and the varied experiences of the participants. The empirical study identified a cluster of elements that consistently occur, thus forming a basis for the user and customer scenario ontology.

An initial ontology was constructed to formally represent user and customer scenarios by inheriting and adapting the presented core ontologies. The domain ontology was systematically integrated into the core ontology by conducting domain-specific research with an angle grinder example.

Future work will focus on automating and validating the generation of scenarios and integrating a machine-readable ontology into a system model. This will allow us to document scenarios and to systematically compare them with one another. Regarding circular products, this will improve the identification and evaluation of relevant edge and corner cases to determine which scenarios are likely to occur and which requirements must be derived for future product generations.

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