Using In-Browser Augmented Reality to Promote Knowledge-Based Engineering throughout the Product Life Cycle

1st Anna Florea
Automation Technology and
Mechanical Engineering
Tampere University
Tampere, Finland
anna.florea@tuni.fi

2nd Andrei Lobov
Department of Mechanical
and Industrial Engineering
Norwegian University of Science and Technology
Trondheim, Norway
andrei.lobov@ntnu.no

3rd Tatiana Minav
Automation Technology and
Mechanical Engineering
Tampere University
Tampere, Finland
tatiana.minav@tuni.fi

***Abstract*—While industry vastly undergoes digitalization, knowledge-based engineering becomes a powerful tool, helping enterprises to operate in context of shorter product life cycles and complex value chains. However, there are several challenges to be addressed in order to make knowledge-based engineering a common industry practice. There is a need for affordable tools, trained professionals, and extended use of outcomes of knowledge-based engineering processes beyond design phase of product life cycle. This article describes how web-based system delivering mobile augmented reality experience in browser may leverage results of product design process implemented with knowledge-based engineering tools in order to integrate information, and support its integrity and consistency for different stakeholders along the product life cycle. The approach relies on use of open standards and libraries in order to insure affordability and ease of integration, which is necessary for wider adoption of knowledge-based engineering among small and medium enterprises.**

***Index Terms*—knowledge-based engineering, product design, product life cycle, WebXR, augmented reality, mobile AR, industrial XR**

I. INTRODUCTION

As complexity of modern economy grows, enterprises are looking for ways to operate efficiently in context of shorter product life cycles and complex value chains. These global trends pose a variety of challenges onto product and process development, operations, and factory deployment [1].

Vast digitalization is seen as key solution to address problems faced by the industrial enterprises. The process is often concerned with extensive data and information capturing and finding new applications for previously collected data. This is often carried out through resource and process virtualization by adoption of cyber-physical systems (CPS) [2] and implementation of digital twins (DTs) [3]. Additionally to improved performance in individual resource operations, these practices strongly support integration across product, process and factory worlds, required for synchronised production operations [4].

Beyond data and information, knowledge-intensive industries seek to capture and re-use product and process related knowledge among various stakeholders, in order to increase their efficiency [1]. The research field of Knowledge-Based Engineering (KBE) emerged to address this need [5], [6]. KBE brings together Computer-Aided Design (CAD) technologies, Object-Oriented Programming (OOP) and Artificial Intelligence (AI) techniques, helping to automate design tasks and capture, retain and re-use design knowledge [5]–[7]. KBE adoption enables knowledge sharing in cross-disciplinary teams [7], it improves transparency and traceability of knowledge [6].

Despite numerous advantages, there are several problems to be addressed in order to make KBE a common practice in industry. Among other, limited pool of trained professionals, and practices of using KBE beyond design phase of product life cycle, stand out. The first challenge relates to the modelling techniques involved in product representations, which require expertise significantly different from the one commonly present among designers and software engineers [5], and can be primarily resolved through training. The latter can be addressed by integrating KBE tools and artefacts into other information systems supporting different phases of a product life cycle.

Present work demonstrates how modern immersive technologies may leverage results of KBE-driven product design to improve product-related services, and end-customer experience. Proposed approach allows to integrate product information from different sources, and maintain its integrity and consistency within applications facing different stakeholders along the product life cycle. The approach is illustrated in web solution, allowing product customization based on KBE representation, providing core order management, and delivering in-browser mobile augmented reality experience for the end-customer to visualize specific order rendered in portable 3D format. The solution relies on use of open standards and libraries, and uses web browser as platform to deliver immersive content. This helps lowering entry barriers

This work is partially supported by K.F. and Maria Dunderberg Foundation and City of Tampere Science Committee.

for small and medium enterprises unable to afford costs and organisational challenges associated with large-scale turnkey solutions [8].

The remainder of the article is organized as follows: Section II provides background for the presented research including state of the art in product life cycle management (PLM), knowledge based engineering, and core technologies enabling presented research; Section III describes rationale behind the proposed approach, and Section IV introduces architecture of the proposed solution; Section V describes practical implementation illustrated with a test use-case. Finally, Section VI summarizes the article with conclusions, brief discussion, and directions for future work.

II. BACKGROUND AND ENABLING TECHNOLOGIES

In context of fast-paced and highly interconnected world, industries undergo digitalization in order to maintain their competitiveness. This may require integration of different multi-disciplinary skills and approaches to manage complexity. The complexity can be addressed on different levels of knowledge representation and integration, as for example by instrumenting data, information and knowledge viewpoints on an industrial system or product [9]. Such disciplines as Product Life cycle Management (PLM) and Knowledge-Based Engineering (KBE), among others, establish foundation for digitalization by providing both requirements and tools for information systems supporting modern industry. As need for cross-domain communication is widely recognised both in field of PLM [1] and KBE [10], this work introduces an approach to integrate product information from different sources, and maintain its integrity and consistency within applications facing different stakeholders along the product life cycle. Use of immersive technologies in presented context serves both improved customer experience and information comprehension among different stakeholders.

This section provides background on core disciplines and technologies enabling this research. First, an overview of PLM, its modern objectives and challenges is presented; then KBE is discussed in relation to challenges faced by PLM and measures leading to wider adoption of the practice; finally a brief overview of augmented reality applications and immersive web is provided, as a state-of-the-art way to visually deliver information.

A. Product Life cycle Management

Modern economy is characterised by shorter product life cycles, which poses multiple challenges on manufacturers, by complicating both design and manufacturing [1]. The benefit of sharing product data and implementing collaborative product development was realized early by the enterprises, leading to development of Product Data Management (PDM) systems. Later, Product Life cycle Management (PLM) systems were developed to include more information about the product and make it available to extended enterprise at different stages of the life cycle [11], helping to improve efficiency of operations.

There are different views on the amount and structure of the product lice cycle stages in the literature. The four stages often mentioned are: *design*, *manufacturing*, *usage*, and *end-of-life* [3]. Some stages are further unfolded and expanded with more specific phases. Overall theses stages can be grouped into three major categories: (1) Beginning of Life cycle (BOL), (2) Middle of Life cycle (MOL), and (3) End of Life cycle (EOL) [11].

The structure of the product life cycle is also influenced by stakeholder's perspective. Two views are described in [12]: *manufacturer's view*, and *end-user's view*. The manufacturer's view then split in two lanes: product and services. This approach illustrates clearly another challenge faced by modern enterprises: the life cycles are not only get shorter, but also more complex as phase boundaries become fuzzy, and some of them become concurrent. E.g. service design or product marketing stages are being initiated before product reaches the manufacturing phase.

For efficient operations, it is important to align product, process and manufacturing life cycles [4] and ensure information flow across domains. One approach suggested in [12] is through implementation of Through-life Engineering Services (TES), facilitating transition of the product and associated information through life cycle phases. However, there are problems, that have to be addressed in order to allow implementation of such services.

Richness of product representation, and availability of product knowledge is uneven along the life cycle for several reasons: design phase is hard to fit into industrial PLM software [1]; digital twin solutions, seen as promising carriers and providers of product and process knowledge, rarely cover stages of the beginning and end of lice cycle [3]; product modelling pursues a different objective at every stage of life cycle, and there are no well-established mechanisms for knowledge transfer; finally, the knowledge is perceived differently among stakeholders and companies, complicating its integration, transfer and re-use [1].

While CAD models remain common link between design, manufacturing and analytic tools [11], wider adoption of Knowledge Based Engineering could help fulfill requirements for integration and collaboration posed by modern PLM.

B. Knowledge-Based Engineering

Additionally to data and information, modern industries aim to capture and re-use product and process related knowledge, making it available for various stakeholders, in order to increase their operational efficiency [1]. The research field of Knowledge-Based Engineering emerged to address this need, being primarily driven by highly competitive and knowledge intensive industries, such as automotive and aerospace [5], [6].

KBE is often defined as field, that combines Computer-Aided Design (CAD) technologies, Object-Oriented Programming (OOP) and Artificial Intelligence (AI) techniques [5]–[7]. It aims to automate design tasks, helps to capture, retain and re-use product knowledge, therefore reducing time and cost of product development. Some researchers distinguish between KBE systems and KBE-assisted CAD, where in latter a KBE language, or some of its capabilities complement CAD functionality [5].

KBE is recognised for enabling knowledge sharing in cross-disciplinary teams [7], and its potential to improve transparency and traceability of knowledge [6]. Its support for automation of designers' tasks fosters creativity and collaboration, and allows access and collaboration over common product data structures [7].

Although this approach bears potential to address numerous challenges faced by manufacturing enterprises, there are several problems to be solved in order to make KBE a common practice in industry. Among other, limited pool of trained professionals, and practices of using KBE beyond design phase of product life cycle, stand out.

The first challenge relates to the modelling techniques involved in product representations, which differ significantly from ones commonly applied by designers and software engineers [5], [13]. The issue can primarily be resolved through training, or by keeping development clearer and closer to problem domain, e.g. as described in [14], where object-oriented approach is applied to abstract Open NX API details.

In order to enable use of KBE beyond design phase, integration of KBE tools and artefacts into other information systems supporting different phases of a product life cycle is needed. It may be often difficult to promote this vision because in case or relatively simple products, design stage is rather clear, while KBE approach would require more effort [6] compared to traditional process. Therefore, despite potential benefits in further stages, the decision may be to not following KBE practices in early stages, hence not adopting it at all. Another common challenge is ensuring the knowledge can be correctly understood by stakeholders along the life cycle [15], ontologies for semantic knowledge representation help to build common context among engineers.

The importance of integration capability of KBE systems was realised early [5], [10], and commercially available software begins to offer interfaces and integration with other off-the-shelf software, and APIs [13]. This work demonstrates how outcomes of design implemented using KBE-assisted CAD can be used further in the product life cycle with support of state of the art immersive web technologies.

C. AR and Immersive web

Immersive technologies, namely Augmented, Virtual, and Mixed reality (AR, VR, MR), find multiple applications in modern industry. These predominantly include professional training, safety training, remote guidance, design and man-machine collaboration.

Professional training allows to practice in lifelike environment and develop required motor skills to perform certain tasks, while reducing use of production resources (e.g. in painting tasks [16]). VR and AR support for assembly operations improves product design, develop faster assembly process, and reduces errors [17]). High immersion VR applied for safety training contributes to improved comprehension and knowledge retention [18]. Remote guidance applications allow to employ knowledge of remotely located experts during field works, troubleshooting and repair tasks (e.g. [19]). In a full feature setup, the person deployed in the field captures a 360° image and uses augmented reality application to receive instructions and annotations from the remote expert. Remote expert uses virtual environment constructed based on the imaging from the field to assist field worker with his tasks. A typical design application would imply working in CAD environment in a VR headset [20], with high-end headsets allowing mixed reality features and prolonged periods of headset usage, significantly shortening the design cycle [21].

In context of present research, important benefits brought by immersive technologies are:

- their support for implementation of trough-life engineering services (TES) [17]
- supporting collaboration and faster customer feedback by providing comprehensive representation equally understood by different stakeholders [22]

Furthermore, as the amount of applications involving immersive technologies grows, there is movement towards application of knowledge-based approach for development of such applications [23], further contributing to harmonisation between design tools, PLM systems, and other enterprise information systems.

Immersive experience can be delivered with a wide range of devices (head-mounted displays, goggles, controllers, tracking devices), and through a variety of software platforms. Some providers build an own closed ecosystems, while other seek openness and interoperability. In highly interconnected world of today, immersive web becomes the next logical stage, since at the moment web is the most widely available platform and allows continuous content update [24].

WebXR initiative was established for providing a uniform abstraction layer for real-time rendering, and access to interaction devices on different XR platforms [25]. The API is being actively developed, and, while early browsers would allow to preview conventional web-sites as flat panes in 3D space [24], it is currently possible to implement web-pages capable of rendering immersive content. WebXR allows close integration of immersive content and textual material, helping to smoothen cognitive and functional seams present in extended reality applications [26].

Mobile AR opens the opportunity to deliver immersive applications without expensive hardware. However, earlier solutions often rely on tags to properly identify spacial elements captured by the camera, and developers face common challenges related to the implementation of cross-platform applications and constraints posed by various mobile platforms and associated ecosystem, as reported in [27].

Following sections will describe how results of KBE-driven product design can be delivered to immersive in-browser web applications in order to improve product-related services and end-customer experience. The approach relies on open standards and widely available tools (i.e. browser) which support ease of development and integration with other information systems, while not requiring additional effort, such as installing specialised application in order to access the service or paper tag handling for marking up spacial features, for the customer to use the tools and services.

III. APPROACH

Product life cycle nowadays becomes increasingly complex: diversity of stakeholders grows, boundaries between life cycle stages become fuzzy, and relationships between stages get more sophisticated, making synchronization very difficult.

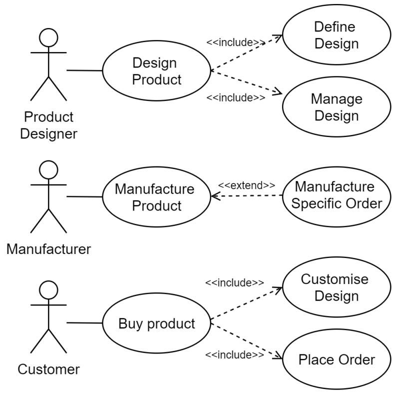


Fig. 1. Example of actors involved in product life cycle and their focus areas.

The use-case diagram in Fig. 1 illustrates some of typical actors involved in product life cycle, their major objectives and processes fulfilling those objectives. Their scopes are rather well-defined and not overlapping. While it enhances clarity of representation, this same fact brings numerous challenges for implementing software systems supporting objectives of individual stakeholder. In particular, due to differences in preferred information representation. This research aims to establish information flows helping to bridge different tools and perspectives on product life cycle leveraging KBE and immersive technologies.

CAD models often serve as common link between design, manufacturing, and analytic [11]. Also, visual representation often is the most comprehensive way to deliver information [24]. This makes immersive applications a suitable context to promote wider KBE application along the product life cycle.

Fig. 2 illustrates the proposed approach in an activity diagram, showing how product representations are being created and used by different stakeholders:

- First, the product design is defined and documented as a collection of documents including KBE definitions of the product, and, specifically, the *customization template* for sales processes and *product definition package* for manufacturer.
- Customization template is then used as foundation for registering customer requirements and generate*specific order definition*.
- Generated order definition, combined with product definition package is used to deliver *order specific CAD model* and proceed with manufacturing.

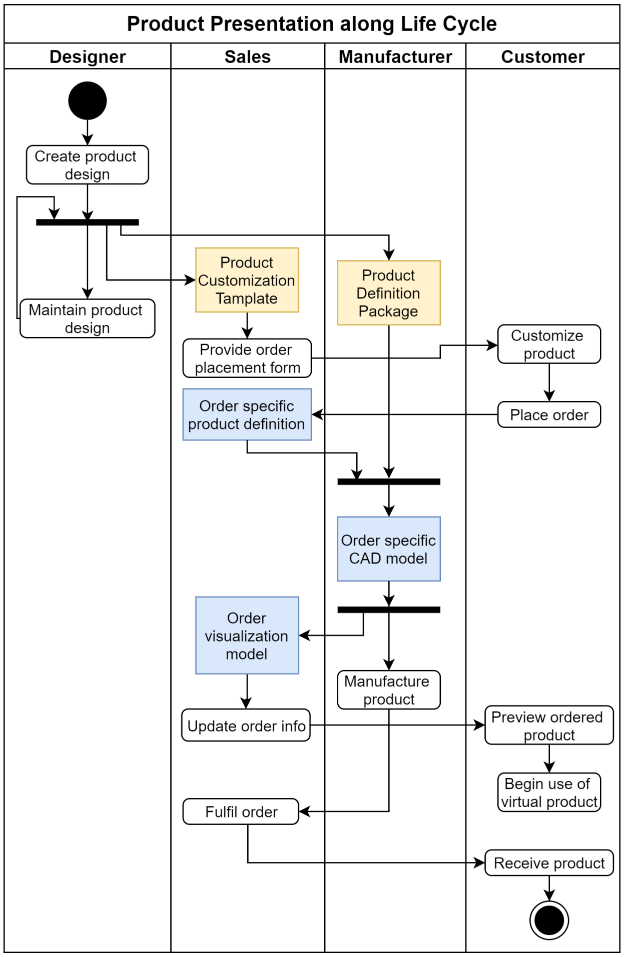


Fig. 2. Product representation and its use among stakeholders.

- The CAD model is then imported into a portable 3D format, e.g. VRML [28], to be used in sales applications for order visualization.
- Once instance specific portable visualization is available, customer can use provided immersive application to give feedback, or start using virtual product to prepare for taking actual product into use (e.g. facilities planing, training, etc.)

From the described workflow, it can be noted, that customers and designers are the parties affecting the structure of product representation, while format transitions are occurring mainly as part of sales/services and manufacturing processes. Following section will introduce architecture to support both types of transitions in representation, and related processes.

IV. ARCHITECTURE

Following the proposed methodology, Fig. 3 presents high-level architecture for providing functionality necessary to implement the approach. Major components are grouped in three layers: *Database*, *Application*, and *Client*. *Administration tools* wrap cross-layer services necessary for infrastructure operation.

Database Layer is concerned with storing two major categories of information: *product design* and *order information*. The way storage is organised for each category is subject to particular implementation. However, the purpose of this layer is to harmonize provision of this information to upper layers.

Application Layer wraps functionality related to management of the information in the data layer, including information upload, update, retrieval and removal. The two components must expose interfaces to each other, to support completeness of information for client applications.

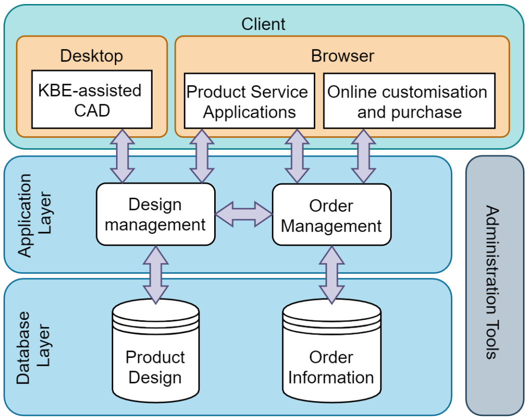


Fig. 3. Logical architecture

Client layer refers to tools and applications built on top of (or integrated with) the application layer. KBE-assisted CAD software used to create product design files is often provided as standalone desktop application, and would primarily use *Design management* functionality to maintain product design documentation. On the other hand, *product service applications* and *product purchase* are suggested to be implemented as web-based systems, where online purchase functionality is built on top of order management, while product services may use both design and order management APIs to implement the business case.

Following section describes implementation of proposed architecture and illustrates systems operation on a test use-case.

V. IMPLEMENTATION

Technical architecture of the implemented system is illustrated in Fig. 4. Product design is realised in form of `*.dfa` files using Knowledge Fusion language of Siemens NX 12.0 PLM software [29]. The CAD model of specific product is generated as `*.prt` file once customer specifies the parameters of the order. For this particular implementation, `VRML` was chosen as portable format for 3D visualization of the product as being a common format for 3D visualization in industrial web applications [5], [11], and supported by available version of the KBE software.

Product definitions in `.dfa` format can be created in any text editor. `Notepad++` was used in case of this work for reason of available syntax highlight feature.

The implementation focused on order information management and functionality allowing to update product definitions with information supplied by customer. The solution uses Django framework [30] for implementing web application for customer to place order and preview 3D model of ordered product using mobile AR experience, while order management on the sales side is accomplished via admin panel of the framework, configured in such a way, that specific user is granted access to navigate and update database entries.

Order entries are stored in PostgreSQL database [31]. The data model of the order management system is defined using means of Django framework. A new order entry is created every time customer places an order. Initially it contains core information about the order including the parameters for order customization. *App Logic* component automatically generates order-specific `.dfa` once the order is placed. *Forms* and *View Logic* help arranging the presentation of UI exposed to the customer via *Templates* (i.e. web pages). Additionally to the information supplied by the back-end, customer UI rendering employs static files, e.g. images and style sheets (CSS).

Product preview via in-browser mobile AR is implemented using WebXR API, and its hit-test feature, allowing user to place a 3D model on a surface, where reticle is pointing. The `VRML` file is loaded and rendered using `three.js` [32]. There are two major factors affecting the availability of the service to the user:

- device's ability to support for mobile XR;
- browser's ability to support WebXR

Alternatively, the experience can be accessed from a computer, with WebXR Device Emulator browser extension. In-browser XR must be provided over secure (i.e. HTTPS) connection, as required by WebXR API.

For the purpose of present research, it was sufficient to use features of the framework's development mode to serve 3D models, and handle order specific product definition. In a production environment, a robust and scalable solution would require a dedicated file server and a database server.

A. Test case

A test case was designed to illustrate the entire process of operating the developed system using a sample product.

For illustrative purposes, the sample product was selected to be a basic cabinet with customization option being the side of the door mount. The product structure is presented in Fig. 5 as object diagram derived from CAD information model proposed in [15]. Cabinet assembly consists of two parts: *body* and *door*. Each part is built of a set of *components*, and door mount type *parameter* passed from *assembly* definition is used to compute some of the door *constraints*. There are three `.dfa` files: one for each part and one for assembly. The assembly file is then used as template to incorporate customer preferences and render order-specific product definition. The approach to `.dfa` development process is similar in structure and workflow to the one described in [33].

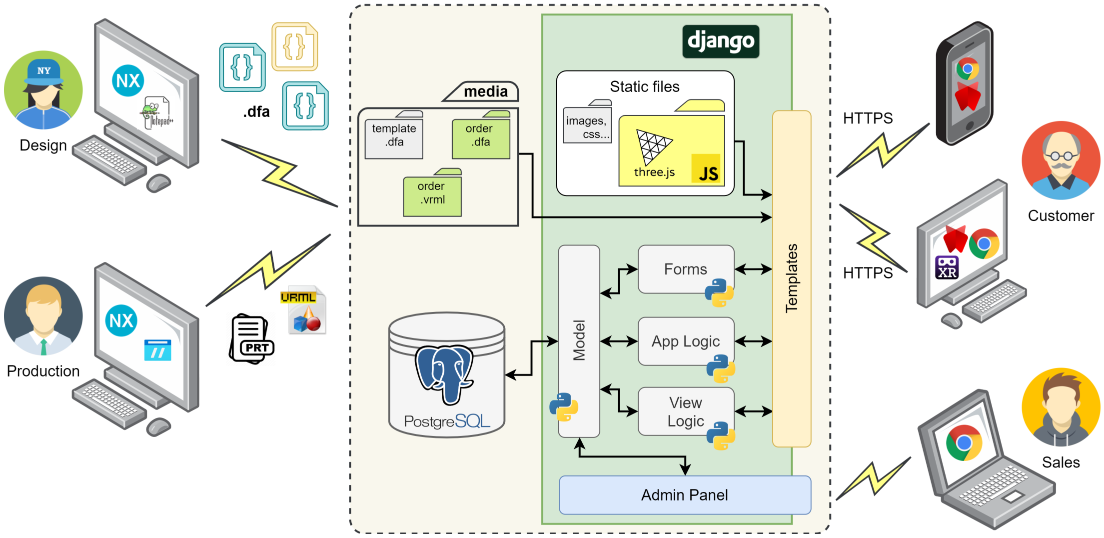


Fig. 4. Implemented solution

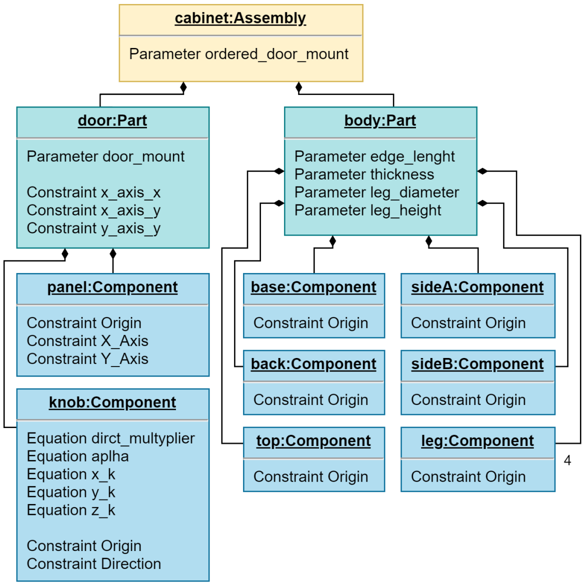
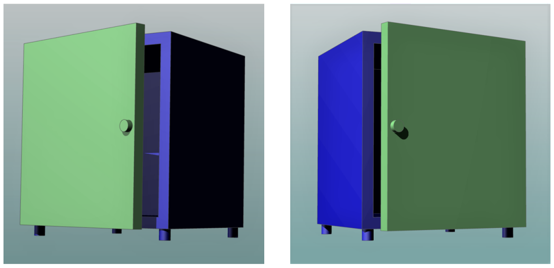
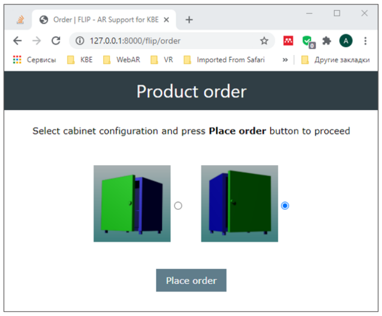


Fig. 5. Object diagram of the product based on CAD Information model from [15]



(a) Door mount option A (b) Door mount option B

Fig. 6. Sample product rendered with Siemens NX

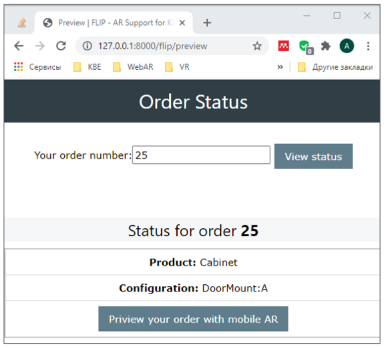


Product order

Select cabinet configuration and press **Place order** button to proceed

○ ●

(a) Order placement



Order Status

Your order number: 25

Status for order **25**

Product: Cabinet

Configuration: DoorMount:A

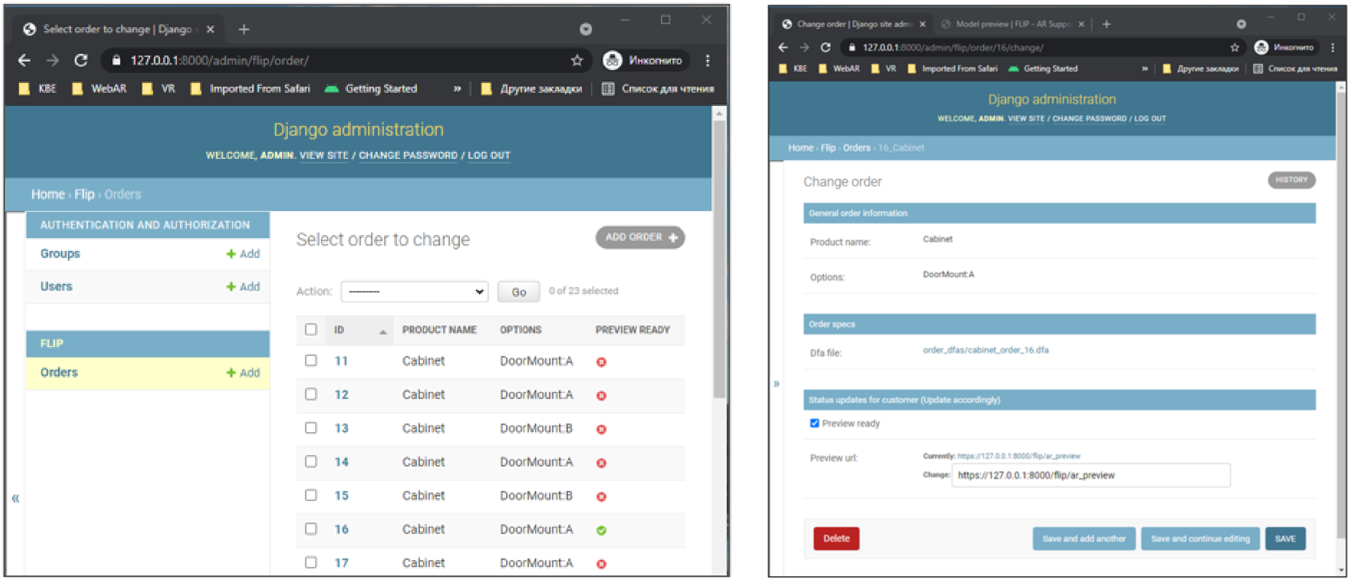
(b) Status and preview

Fig. 7. Customer order UI

Fig. 6 contains visualization of the product rendered with Simemns NX software based on two specific orders, to illustrate available door mount options.

The images are used to assist user in selecting correct option while placing order, as illustrated in Fig. 7 (a). Similar images are used to illustrate the ordered product while dedicated 3D model is ready. Once order visualization is ready, customer receives a link to order preview(Fig. 7 (b)).

Once order is placed an entry is created in database.



Select order to change

Action: --------- 0 of 23 selected

☐	ID	PRODUCT NAME	OPTIONS	PREVIEW READY
☐	11	Cabinet	DoorMount:A	☒
☐	12	Cabinet	DoorMount:A	☒
☐	13	Cabinet	DoorMount:B	☒
☐	14	Cabinet	DoorMount:A	☒
☐	15	Cabinet	DoorMount:B	☒
☐	16	Cabinet	DoorMount:A	✓
☐	17	Cabinet	DoorMount:A	☒

Change order

General order information

Product name: Cabinet

Options: DoorMount:A

Order specs

Dfa file: order_dfas/cabinet_order_16.dfa

Status updates for customer (Update accordingly)

☑ Preview ready

Preview url: Currently: https://127.0.0.1:8000/flip/ar_preview
Change: https://127.0.0.1:8000/flip/ar_preview

(a) Order list (b) Order details

Fig. 8. Order management UI

Authorised user from sales or production services can see the list of orders (Fig. 8 (a)). Each order can be accessed to obtain order specific `.dfa` file or update product status when visualization is available (Fig. 8 (b)).

When customer clicks on the button to preview order in AR, he is taken to the page checking whether current device allows AR, and if it is possible user is prompted to proceed to the experience. Then it is possible to use smart phone (or in-browser device emulator) to locate a surface and then place the 3D model onto the surface by taping on the reticle. An example of cabinet model placed using the tool is shown in Fig. 9. The model can be relocated by pointing mobile device to a new location and taping on the reticle once it appears.

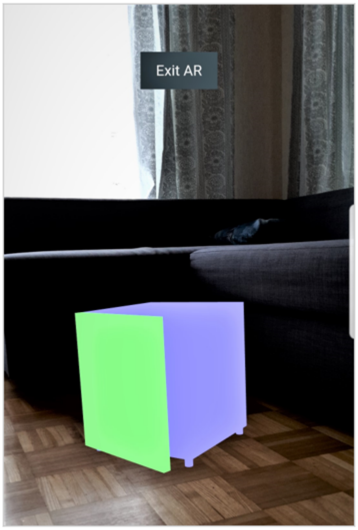


Fig. 9. Fragment of screenshot of cabinet preview in AR

The described implementation relies on software tools commonly used in the industry, while also taking advantage of affordability and convenience of web, as platform to deliver new functionality via familiar tools and interfaces.

VI. CONCLUSIONS

The disciplines of PLM and KBE provide foundation for building tools and processes to fulfil needs of manufacturing enterprises in their effort to keep up with increasing complexity of modern economies. Establishing information exchange across different product life cycle stages, and ensuring comprehensive knowledge representation relevant to each stakeholder is essential for making KBE approach a common industrial practice.

Presented work demonstrates, how immersive applications can support and promote use of KBE outcomes at different stages of product life cycle, as it relies on CAD representations, which serve a common link across processes, and involves visual representation, which is seen as most comprehensive form of information delivery.

Implemented system involves commonly used industrial tools as well as widely and openly available web technologies, supporting affordability of the approach and allowing to cover broader range of stakeholders.

While present effort established connections across stakeholders and built grounds for seamless integration of customer inputs into KBE-based product representation, future effort must be put into expanding the practice further along the life cycle, into product usage and disposal phase, and establishing path for supplying learnings from later stages back into product design processes.

As far, as technical aspects of the solution are concerned, a production solution for a specific business case will have to extensively consider such aspects as user experience, quality assurance and system scalability, along other aspects. However, as mentioned in [23], dimensions of requirements for industrial immersive applications do not differ from the ones for the other information systems being developed and tailored for a specific company.

There is no doubt that immersive technologies bear multiple benefits for industrial use. Therefore, it is important to create meaningful applications delivering value to the end-user while choosing right medium, which is often difficult due to diversity of available hardware and interaction modalities. While in-browser immersive experience appeals to developers as affordable approach allowing to reach wider audiences, WebXR is currently evolving and developing very fast. The need for regular update and maintenance at the moment of writing the article may come as disadvantage. As some studies show, the nature of bugs in WebXR enabled applications differs from traditional web applications, and errors are often caused by mishandling diversity of devices and user interactions [34]. The severity of these challenges will diminish as technology matures.

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