# Integrating the user experience throughout the product lifecycle with real-time simulation-based digital twins

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# INTEGRATING USER EXPERIENCE THROUGHOUT THE PRODUCT LIFECYCLE WITH REAL-TIME SIMULATION-BASED

# DIGITAL TWINS

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**Abstract**

Product development of complex machines is moving from the development of technical features to an emphasis on user experience throughout the product lifecycle. The advent of new real-time simulation techniques is enabling end-user participation in product development and active collaboration throughout the entire product lifecycle. Using an example of a real-time simulation of a forklift, this paper describes an approach to integrate the needs and requirements of the end users throughout the product lifecycle. In practice, this cooperation is facilitated by accumulating user experience in a virtual reality environment using real-time simulation of the multibody system based forklift. The paper discusses tools and procedures that should be included in user experience driven product development with digital twins to integrate user experience into the product lifecycle and describes how the new approach can influence conventional business processes and customers' purchase decisions.

## Introduction

Sustainable business models stress the need to increase customer value throughout the product lifecycle from product design and development to production, service and disposal. In traditional product development using conventional technologies, users have access to physical prototypes, but they can not experience the product during its design and development stages. Accordingly, conventional product development does not involve users in decision making throughout the entire product lifecycle. This can result in expensive and unsuitable products that do not fully meet user needs (Tao, et al., 2019) (Armendia, et al., 2019). Utilization of digital technologies such as physics-based real-time simulation of the physical product potentially allows users to be involved throughout the product lifecycle from product design to product disposal.

Previous literature on digital twins has focused primarily on modeling and data management aspects. Work considering the modeling perspective of digital twins has generally focused on the product and processes without considering the physics and connections to the physical counterpart (Tao, et al., 2019) (Armendia, et al., 2019). Data management studies, in turn, have mainly used digital twin information to describe product processes and information flows. While providing valuable information, important elements of user experience are absent in such studies.

A multibody-based digital twin involves dynamic solution of the equations of motion of the physical product. It can provide information about the physical counterpart as a single source. This information can be shared with end-users and customers to co-create and increase the customer value of product-service systems during the various stages of the product lifecycle. In addition, virtual reality (VR) or augmented reality (AR) tools can be integrated with a multibody-based digital twin to enhance user experience (UX) in the immersive environment. Thus, users and potential users can experience working cycles of the real-world counterpart with VR/AR technologies and assist digitally in efficient management of product development processes. The engagement of end-users and customers in product development and enhancement processes can generate innovative ideas and provide valuable insights enabling changes and improvements in future products and related services (Tseng, et al., 2010). Moreover, taking into account user experience and customer needs throughout the whole product lifecycle by UX and data generation with multibody-based digital twins may enable radical innovations in competitive markets (Orcik, et al., 2013).

An industrial need highlighted in Chapter 2 is the necessity to explore the potential of digital technologies (e.g. VR) for testing UX of end-users and customers and for co-creating customer value in a product and/or service. This chapter focuses on user experience with VR technologies in real-time simulation based on multibody system dynamics. Thus, the objective is to explore the role of users in multibody-based digital twin utilization throughout the product lifecycle, including design, production, service, and end of life stages. To this end, a real-time simulation of an industrial 3W 2.0-ton EVOLT 48 counterbalance forklift truck using VR tools is described and a methodology is proposed that enables the integration of user experience throughout the different stages of the product lifecycle.

The rest of this chapter is structured as follows. Section 2 describes the multibody-based digital twin and highlights key literature related to product lifecycle analysis, user experience and co-creation of product value through UX. A methodology that can enable the integration of user experience into the product lifecycle using multibody-based digital twins is then introduced. Next, a case study of a 3W 2.0-ton EVOLT 48 forklift truck is taken as an example to illustrate multibody-based digital twin UX integration into the different phases of the product lifecycle of a forklift truck, such as design and development, production, service and disposal. Conclusions are drawn in the final section.

## Related research

### *Multibody definition of a digital twin*

The digital twin is at the core of digitalization of product development offers a way to simulate the behavior of a product over its lifecycle  (Tao, et al., 2019) (Grieves, 2014). As claimed by the National Aeronautics and Space Agency (NASA), the concept of a mobile machine twin was first introduced in 1960 during the Apollo program (Tao, et al., 2019). In that example of a twin, engineers used the physical space of a space vehicle to analyze conditions in the space vehicle. With the development of modern computer systems and simulation methods, the physical space is being replaced by a simulation model or virtual space. The simulation model is a representation of a physical system that can execute real world behaviors in a computer simulation. Further, advanced information and networking technologies such as the Internet of Things (IoT), artificial intelligence (AI), big data and cloud computing enable real-time information transfer between the physical and virtual spaces of a digital twin (Tao, et al., 2019). Considering these novel data transfer technologies, Grieves (2014) introduced three dimensions of the digital twin, namely the physical space, the virtual space and the connections between the two spaces. Recently, Tao et al. (2019) added data and services as a dimension of the digital twin. These definitions, however, do not consider the physics of the real world and user involvement in the simulation model of the digital twin.

A multibody model can be seen as a physics-based digital replica of the physical world that can simulate working conditions and update its status continuously from multiple sources. The solution of a multibody model can be synchronized to real-time operations. The model can be used throughout the product lifecycle as a real-world counterpart. The multibody model may include details of hydraulics, electrics, mechanical actuators, tires, and physical contacts of the system. Additionally, the use of multibody equations of motion with state estimation theories such as the Kalman filter permits digital twin data to be generated that cannot be measured directly with sensors for technical and economic reasons (Sanjurjo, 2016). By utilizing identical controls to the real-world and Human Machine Interface (HMI) systems, a multibody model closely involves users in the working cycles. The use of immersive methods in the simulation models allows stakeholders to evaluate, optimize and predict the states of the physical space of the digital twin. When the digital twin has connectivity to the real-world, i.e. where data is exchanged, digital business models can be identified to create new revenue streams and value for customers (Donoghue, et al., 2019).

*Product lifecycle*

The business literature presents numerous decision and innovation process models that describe how companies develop or should develop new products or services. Koen (2002) divides the innovation process into three areas: the fuzzy front end, new product development and product commercialization. In most models, user experience (UX) in product development is mainly focused on the new product development phase. However, the phase after commercialization of a product can also be important for enabling companies to understand how products are used (Varsaluoma, 2018). For example, companies can benefit from understanding how to develop a positive user experience and analyzing how these goals for user experience are expressed by their customers over time (Varsaluoma, 2018).

The different phases of the product lifecycle are defined in the literature in different ways with various terms and categorizations. Grieves defined (2005) Product Lifecycle Management (PLM) as an information-driven approach integrating people, processes/practices and technologies across the entire product lifecycle, i.e. design, manufacture, deployment, maintenance, removal of product and final disposal. Stark (2006) introduced the manufacturer's and user's viewpoints into the product lifecycle. The manufacturer of a product sees a product's lifecycle as starting from generation of the idea of the product to its production, realization, support and services, and ending in the product's retirement. The user of a product sees a product's lifecycle as starting from the acquisition of the product and its usage and ending at the moment when the product stops being used and is disposed. Terzi et al. (2010) divided the product lifecycle into three phases: Beginning of Life (BOL) – developing and delivering the product, Middle of Life (MOL) – operating and maintaining the product, and End of Life (EOL) – removing the product from support and service in a controlled fashion. Donoghue et al. (2017) have identified that companies may also have a Product Lifecycle Management framework. This framework includes three lifecycle phases and the interactions between the different product layers that need to be managed with different business processes, see Figure 1.

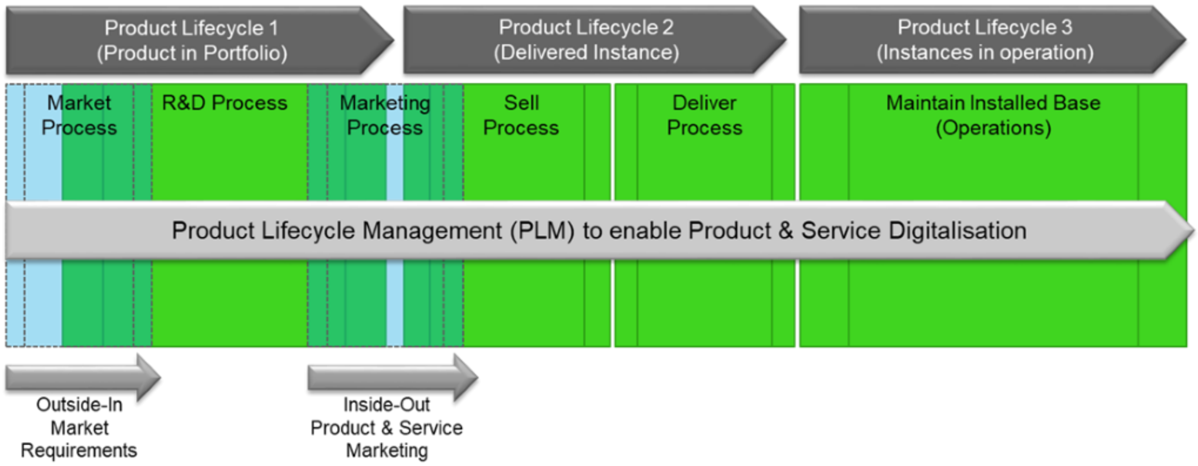


**Figure 1.** Product lifecycle management framework (Donoghue, et al., 2017).

*User experience (UX)*

New products may fail to meet customers' and end-users' requirements. To avoid such market failures, product values should be co-created by the users and companies through efficient interaction between the product developers and users in innovation activity (Orcik, et al., 2013). In such co-creation, the users interact with the product and give opinions about the performance of the product based on their knowledge, skills and experience at the product development stage (Orcik, et al., 2013). The experiences of users during this interaction, termed user experience (UX), become a key factor for adding product value and achieving competitive advantage (Hildén, et al., 2016). Consideration of UX in new products can produce innovative ideas and allow industries to discover new dimensions of their products and services. Consequently, a UX-based approach can enhance companies' competitiveness and profitability and improve the quality of the products and services offered (Orcik, et al., 2013). It should be noted that UX not only comprises the pragmatic functions of the product but also the affective and cognitive demands of end-users and customers. Affective and cognitive demands are the psychological needs, cognitive capacities, choices and emotional responses of the users (Zhou, et al., 2013).

*Co-creating product value with UX and multibody based digital twins*

Several researchers have implemented digital twins in immersive and interactive environments as a part of efforts to improve user experiences at different stages of the product lifecycle. For instance, an Augmented Reality (AR) system was used in Schroeder et al. (2016) to display digital twin data at the marketing stage based on the concept of a cyber-physical system (CPS). In the work, end-users and customers had access to physical machine sensor data via web services and could explore an industrial plant and its devices in real-time. In work by Laaki et al. (2019) considering the product service stage, users were able to perform remote surgery operations by employing a digital twin of a robotic arm in a Virtual Reality (VR) system. In the study, the VR system was used to engage users to perform a surgery operation in the virtual environment. A physical robotic arm executed a similar operation in the real-world. A 4G network transmitted the data between the physical and virtual spaces of the digital twin. In other work, VR and AR systems have been used in engineering (Posada, et al., 2015), art (Rechowicz, et al., 2018), gaming (Kosmadoudi, et al., 2013) and architectural (Schroeder, et al., 2016) applications at different stages of the product life cycle. These digital twins were however developed to serve specific user needs, and they do not include the physics in the simulation models. For complex machines of the type considered in this paper, studies investigating the co-creation of products using UX and digital twins have been limited to the product design and development phase (Auricht & Stark, 2015). To fill this gap, this study utilizes a multibody based digital twin that can be used to include customers and end-users throughout the product lifecycle and that enables UX information to be generated with real-time simulation of a complex machine.

**Enabling user experiences in the product lifecycle with an immersive multibody-based digital twin approach**

Figure 2 presents a multibody-based digital twin methodology that could be adopted to include user experiences throughout the entire product lifecycle. The steps of the methodology are explained in further detail in the subsections below.

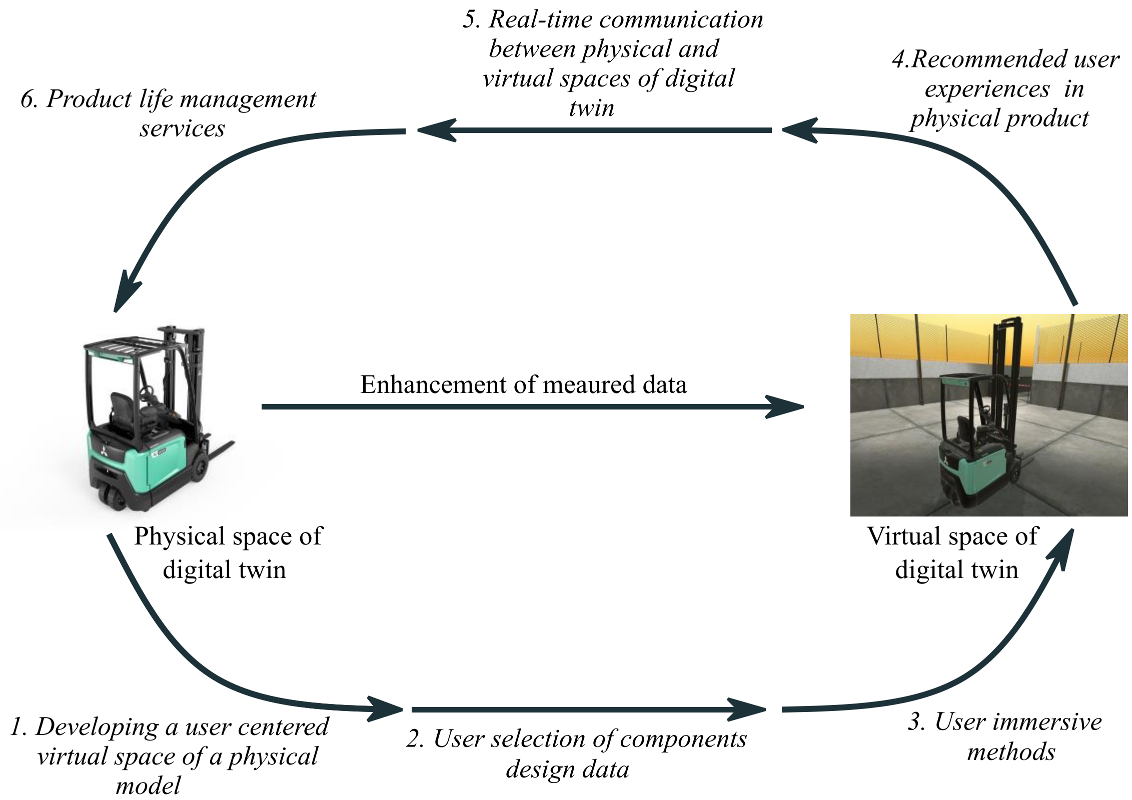


**Figure 2.** Methodology to enable UX integration into the product life cycle using multibody virtual and physical spaces of a digital twin

*Developing a user-centered virtual space of a physical model*

The multibody simulation model presents all the components and sub-components of the physical model in a computer model. Like the physical system, the virtual duplicate may include rigid and flexible bodies, hydraulics, electric drives, tires, power transmissions, forces, frictions, particles, and the Human Machine Interface (HMI) and controls. The multibody equations of motion include contact and collision models to describe the dynamics of the simulation model. Following advances in multibody formulations, standard computer systems can solve the complex equations of motion in real-time at a time step of 0.5-2 milliseconds (ms) (Jalon and Bayo 2012) (Jaiswal, et al. 2019).

In short, the multibody model simulates the realistic behavior, properties and physics of the real world in real-time. The real-world counterpart, i.e. the virtual twin simulation model, can exist even before the manufacturing of the actual product in the product development and commercialization stages. Combined with sensor data from the physical space, the multibody simulation model guides users throughout the product lifecycle and enables them to evaluate, optimize, control and predict real-world working cycles in real-time.

*User selection of component design data*

Design data of different components and sub-components of a multibody model are collected, combined and analyzed. Such data comprises positions, masses and inertias of bodies, hydraulics, electrics, power transmission system parameters and friction coefficients of the physical systems. Combining data from different sources enables designers to analyze product performance as per user needs in the multibody simulation model. At this stage, end-users and customers participate in the design process and test the features of the product in the simulation model. The user comments on the multibody model can help designers discover relationships between design data and user preferences. The companies may also be able to use these relationship patterns in future products.

*Immersive methods for generating user input*

In addition to computer system controls, multibody-based digital twins can engage end-users and customers by using immersive virtual environments. To be able to assess the HMI and usability of the physical system, the multibody-based digital twin can be integrated with gaming controls, simulators, VR, AR, mixed reality (MR) and haptics. Using these external devices, the users' senses and perceptions are fully immersed in the virtual environment. Consequently, the multibody-based digital twin can perform the pragmatic functions of the product and meet the affective and cognitive needs of end-users and customers.  A number of immersive environments enabling technologies are discussed below.

*Simulator or motion feedback platform*

Real-time simulations can be done in simulators to provide end-users and customers with a cockpit experience. Physical system controls and ergonomics can be constructed on the simulator such that the HMI of the simulation corresponds to real world experiences. The simulator machine can also be equipped with a motion feedback platform to provide the feeling of the terrain path in the simulation (see Figure 3). Additionally, as can be seen in Figure 3(b), using a cave-like environment, where extra display screens on the moveable platform immerse the human body in the simulation, can give users a more intensive visual experience. This virtual environment can give more realistic feelings to users with VR/AR glasses.


*a) Simulator platforms with and without motion feedback*

*b) Highly immersive cave-like environment with motion feedback platform*

**Figure 3.** Involving users in the virtual multibody model on the simulator

*VR, AR, mixed reality glasses, leap controllers and haptics*

End-users and customers can be immersed into virtual world through a head mounted display (HMD). These VR, AR and mixed reality glasses take the human inside the virtual space. Through these external tools, the users can have a deeper understanding of the real-world counterpart and its environment. Many types of HMD are available on the market, such as the HTC Vive system, and Oculus Rift and XR-1 glasses. Figure 4 lists some immersive devices that could possibly be integrated into a real-time simulation to provide a user-immersive environment. Leap controllers and haptics further enable users to experience different parts of the body in the simulation environment.

*a) Augmented reality technology*

*b) Haptics*

*c) High resolution virtual reality glasses*

*d) Virtual glasses with leap controllers to experience user hands*

**Figure 4.** Examples of user immersive technologies for virtual environments *(Augmency, 2018)* (*VIVE, 2020)*

*Manufacturing of the physical product*

Manufacturing of the physical product can be planned based on the experiences and recommendations of users of the virtual product. User experiences related to the dynamics of the simulation model are added to the physical product by means of actuators, controls and sensors. The physical model may contain hydraulics, electrics, pneumatic and mechanical actuators, and tires to execute requests made by users of the multibody model in the immersive environment. Sensors can collect physical product data and input it into the simulation model. This model can be used in the service stage of the forklift, as shown in Figure 2, where the virtual replica of a physical 3W 2.0-ton EVOLT 48 forklift in a VR environment is presented. User experiences in the physical version of the forklift can also be tracked in the reference link(EDiA, 2019).

*Real-time communication between the physical and virtual spaces of the digital twin*

Before the release of a product developed based on user experiences, the physical and virtual spaces need to be connected to each other so that digital twin information can be used in different phases of the product lifecycle as per end-users' and customers' needs. Network communication, cloud computing and network security are the key enabling technologies for transmitting data back and forth between the physical and virtual twins. The physical product sensor data is stored in data cloud storage using network technologies such as quick response

(QR) code, radio frequency identification (RFID), barcodes, wireless fidelity (Wi-Fi), Bluetooth etc., and the data can be accessed via the 4G network. The multibody model enables end-users and customers to monitor, coordinate and control the real world of the digital twin. This data communication must be secured for successful management of product lifecycle related services.

*Product life management data*

The multibody-based digital twin generates big data during the service and end of life phases, and this data can spur development of new product-related services. The data can include product component data, product-environment interaction data, environment data, product user data and control data. As mentioned earlier, the data can be used in the real-world counterpart with the aid of sensors and IoT services in real-time. By using VR/AR immersive technologies, the multibody based digital twin enables users to predict, optimize, simulate and experience the states of the physical space with contacts and collisions in the environmental during the product's life. For instance, product component data can notify stakeholders of the need to take actions related to predictive maintenance of the product. Similarly, using product state data, more precise decisions about the reuse or retiring of a product can be taken. Additionally, industry can utilize user experience history from the lifecycle of previous multibody-based digital twins in future products and other projects to gain competitive advantage.

*Enhancement of measured data*

Due to integration of the equations of motion with a state observer estimator, the multibody simulation can provide information about the internal states of the system based on a smaller amount of sensor data from the physical system (Sanjurjo, 2016). In this way, the multibody-based digital twin can provide detailed information about the state of the physical system, which in some cases can reduce sensor costs. In this manner, the multibody-based digital twin can reduce the cost of management of many digital product processes compared to conventional digital twin technologies. For instance, accurate information about tire friction of a road vehicle can be obtained, from which it is possible to predict wear and tear of tires.

**Industrial case study: User experience in different phases of the product lifecycle with a multibody digital twin**

The case company of this study wants to explore the possibilities of using digital technologies, especially digital twins utilizing VR technologies, to integrate end-users and customers into management of the product lifecycle. The case company has identified the following challenges:

- Co-creating new products with users to strengthen the customer feedback loop and include innovative ideas in the final product.
- Product lead time to market can be long as the manufacturing, testing, remanufacturing, and retesting of the physical prototype demands a significant amount of time, effort, and money.
- Exploring materials and manufacturing solutions of the product by testing the product in different working environments.
- Provision of repair and maintenance services to end-users and customers to gain competitive advantage in the market.
- Decision making with users about the reuse or disposal of products in an eco-friendly way for a safe working environment.

In this study, these challenges have been addressed by developing and implementing a multibody-based digital twin of a 3W 2.0-ton EVOLT48 counterbalance forklift. A parameterized real-world counterpart of the multibody forklift model was prepared using multibody equations of motion. The digital model included actual physical dimensions, hydraulics, electric and mechanical actuator data, tires and contact parameters for realistic user feeling in the real-time simulation. A motion feedback platform and VR/AR immersive methods tightly integrated the twins and allowed end-users and customers to experience functions and behavior of the forklift in the digital world. The following subsection details the integration of users in the forklift lifecycle using a multibody-based forklift simulation model.

*New product development approach: User co-creation of a new forklift mast system in the virtual space*

The main challenge faced by the case company is to shorten the product development process while simultaneously including end-users and customers in co-creation of product value. The case company currently uses a physical prototyping method to develop new products. In this approach, end-users and customers test physical prototypes after manufacturing, which increases product development cost, and the effort and time required. Customers and end-users can only comment on the performance of the product after purchase, which extends the customer feedback loop. The multibody simulation permits end-users and customers to directly test the new product developed by the company. This user experience driven approach was used in the development of the 3W 2.0-ton EVOLT48 counterbalance forklift. The approach is presented schematically in Figure 5.

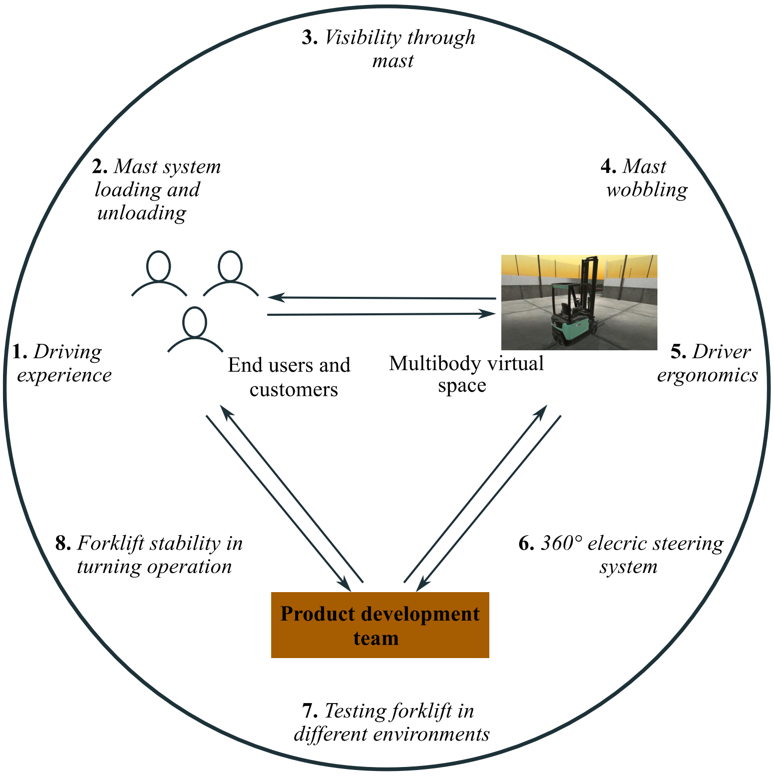


**Figure 5.** User experience-driven product development of a 3W 2.0-ton EVOLT48 counterbalance forklift using multibody real-time simulation. Important user experiences related to forklift are also numbered in Figure 5. Two sided arrows highlight integration of end-users and customers through multibody virtual space with the product development team.

As can be seen in Figure 5, end-users and customers directly participate in the product development process and comment on the performance of the forklift. Important UX elements related to the forklift are driving experience, mast system loading and unloading, visibility through the mast system, mast wobbling, 360° electric steering, forklift stability, forklift controls and ergonomics, and the working environment of the forklift. The forklift can lift a maximum load of 2000 kg. Driving experience includes forklift forward and backward movements, and braking action. The stability of the forklift under minimum and maximum loads while turning was tested by users in the simulation model. Another UX-related aspect is smooth reduction of speed going into corners and smooth increase on exiting corners. Agility and the ability to turn quickly as well as turning circle are also important. Finally, the visibility and clarity of the displays used is a further important aspect of user experience. The loading experience is how the mast behaves under load. An important behavior mentioned was the smoothness and accuracy of the lifting. Smoothness corresponds to continuous movement or extension of the mast when the operator uses the switches. Additionally, mast wobbling provides users and customers with a realistic experience in the real-time simulation.

*Commercialization: User testing of the parameterized model in different environments*

Product lead time to market of the case company is long due to the physical prototype culture as production and development of iterations of the physical prototype take time. Furthermore, new products are often introduced after a significant drop in product sales. This culture hinders the case company from achieving a sustainable business model in a competitive environment.

Implementing multibody digital twin, as mentioned in Figure 6, involve the end-users and customers with the 3W 2.0-ton EVOLT forklift at the marketing stage using various versions of the product. From many options, end-users and customers select the best combination of forklift machine and mast system on the motion platform. Using VR/AR immersive technologies, end-users and customers test the new product in the working environments as per their needs and future requirements. By respecting the user choices and needs in the virtual model, the case company avoids physical prototype culture. This reduces the product lead time to the market. Additionally, i.e. product commercialization, the use of the simulation for marketing, selling and training can be seen as offering improvements from both the cost and time perspective and creating a positive customer experience (Donoghue et. al., 2017). The added value is to offer a continuous journey from marketing to delivery and training (Donoghue et. al., 2017).

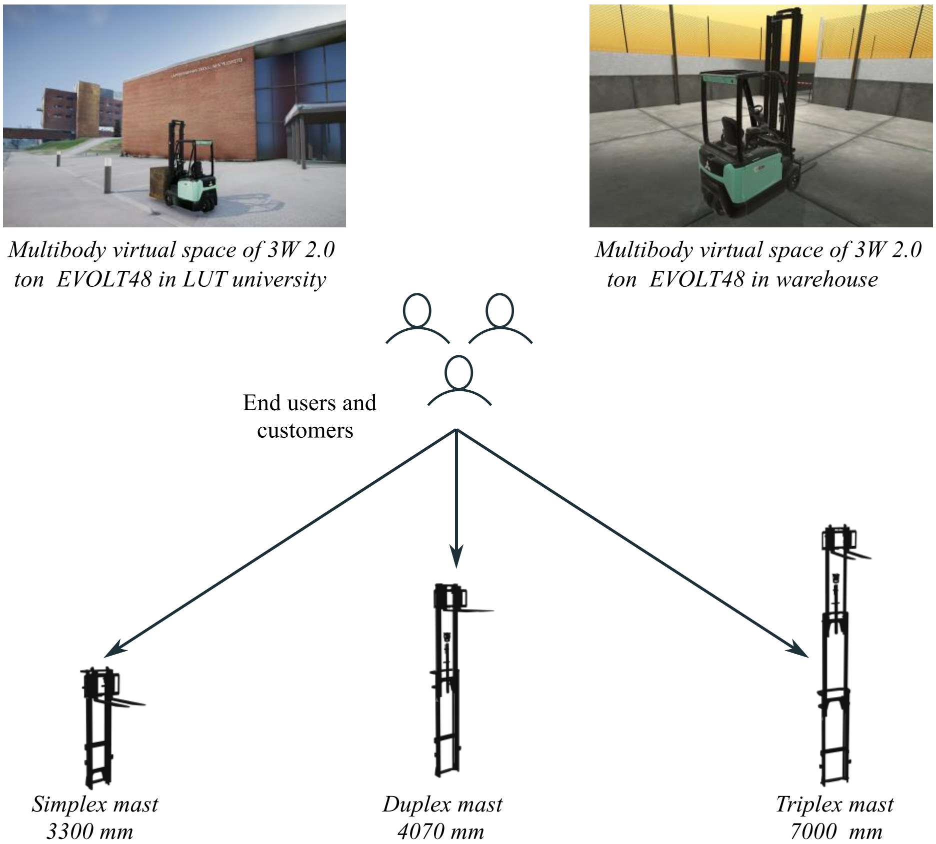


**Figure 6.** Accelerating the marketing process of the 3W 2.0-ton EVOLT 48 forklift by using a multibody simulation model.

*Manufacturing: Utilizing the user-based multibody model in production*

Using the multibody digital model, industrial companies can prepare materials charts and machine components for use in the simulation world. The end-users and customers choose optimum materials and components when designing a machine configuration as per their needs in the working environment. Based on the selected configuration, parameters change in the real-time simulation. In this way, end-users and customers can test a wide range of different configurations on the simulator. Following selection by the user, the manufacturing company orders appropriate raw materials and components for manufacturing and production of the final product. Further, end-users and customers can track the status of manufacturing of the physical space via an online portal with a private radio frequency identification (RFID) or barcode provided by the manufacturing company.

*User-related product services in the operation phase: Updating the virtual space of the digital twin with real-world information*

Based on the exact machine dimensions and features selected, it is possible to support users in the commissioning and delivery of the physical version of the digital twin. In addition, the real-time multibody simulation driven motion feedback platform can be used to provide training services even before the start of manufacturing of the physical product. As mentioned earlier, a real-time secured connection is built between the virtual and real-world spaces of the digital twins to monitor, optimize and predict field data. For instance, decisions about predictive maintenance of hydraulic systems can be made by collecting sensor field data. In such an approach, the lifecycle efficiency online system analyzes the sensor data and calculates the lifetime of the hydraulic cylinders (Mevea, 2019). Similarly, the digital version of the twin can be used remotely to monitor and control real world operations in difficult and dangerous working conditions (Mevea, 2019). In this way, the multibody-based digital twin will ensure the safety of workers and improve quality, productivity and performance of industrial operations. The overall cost of multibody digital driven product processes can be much less than conventional product processes.

*End of product life: Retiring the product based on user data generated in the digital twin*

As noted earlier, one challenge when using conventional methods is that users and manufacturers do not have a direct relationship while the product is being developed and used. Manufacturers are compelled to take independent decisions about the retirement or repairing of the physical product. Real-time simulation enhances product lifecycle management by building a relationship between the manufacturer and users as the multibody-based digital twin continuously receives real-time updates from the real-world from sensors, IoT, cloud computing and network security services. Manufacturer can thus inform users about poorly functioning parts and, if necessary, the users and manufacturer can agree about the possibility of repairing the physical version of the multibody based digital twin. Finally, if the physical product is no longer fit for further work, users and manufacturers can together agree a retiring date for the physical product to ensure a safe working environment.

## Conclusion

Utilization of a multibody based digital twin makes it possible to integrate end-users and customers into the various phases of the product lifecycle in a straightforward manner. The direct involvement of users in the product development process enables companies to co-create appropriate and competitive products. Replacing the physical prototype culture can reduce considerably the product lead time to market, which, in turn, enables companies to gain competitive advantage in the market. Real-time communication between the physical and virtual parts of digital twin, in turn, can enable companies to optimize the working cycles of the physical product. Additionally, for work in dangerous conditions, end-users and customers can control the working cycles of the physical product remotely using the multibody-based digital twin.

The valuable real-world data generated from integration of the physical and digital twins enables monitoring of degrading or malfunctioning parts of the physical product, thus allowing them to be used optimally before being repaired or replaced, which reduces maintenance costs. Timely removal of degrading parts can also lead to reduced energy consumption. Furthermore, prediction of breakdown or maintenance needs can help end-users in decision making and reduce downtime. The multibody-based digital twin can be integrated into different information technologies such as IoT, big data, artificial intelligence, machine learning, cloud computing etc. to provide additional services. Moreover, the multibody digital twin data can assist stakeholders dispose of products in an eco-friendly and efficient way. Finally, multibody digital twin and user data can be used by companies to develop more user- and environment-friendly products, as well as products that are compatible, competitive and adaptable. Hence, the engagement of end-users and customers throughout a product lifecycle by utilization of a multibody digital twin approach can enable companies achieve sustainable business models in a competitive market environment.

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