Realising co-development in digital-twin business ecosystems for heavy machinery

Abstract

A fundamental building block of digitalisation is the digital twin, a virtual duplicate of an entity that is accessible to relevant internal and external stakeholders and updated throughout the system's lifecycle to help decision-making associated with development, adaptability, production, and service. This chapter examines the application of the digital twin to achieve more effective development of a plywood panel repair line, a machine system featuring precision dynamics and mechanical complexity, by enabling better cooperation among the multidisciplinary engineering team and other stakeholders. For this case example, a digital twin was developed for the system's most critical elements: the vacuum conveyor, the defect detection system, and the repair area. Well-timed communication among members of the product team is essential to achieving rapid design iteration for complex systems such as these. Realising the example revealed challenges with respect to coordination, complexity and interconnectedness, and the management of data and software intensiveness that were addressed via digital twin data management, the use of surrogate models, and virtual prototyping. Results suggest that cooperative development within a digital twin business ecosystem enables more informal controls that promote initiative and creativity from development personnel and leads to faster and more effective product development. When the simulation methodology allowed correct automation codes running already in the testing phase, user interfaces, digital service data collection and reporting could be done in advance, facilitating on-time feedback on the development. Thus, the proposed approach will fasten the supply time significantly.

Keywords: digital business ecosystem; digital twin; co-development; manufacturing; heavy machinery

1 Introduction

This study aims to examine the co-development of heavy machinery in digital twin business ecosystems. The business environment for heavy machinery manufacturing is in the process of fundamental digital transformation (Schallmo & Williams, 2018) as a response to both global shifts in market need and the availability of new technologies. The market has seen a rapid shift towards more sustainable solutions, improved resource efficiency, and closer ecosystem collaboration (Onaji *et al.*, 2022). At the same time, digital technologies are redefining decision-making, the roles and responsibilities given to humans and machines in processes, and the cost and effectiveness of innovation, coordination, and control (Teece, 2018). The result is a continuous increase in software intensity and a more prevalent use of artificial intelligence in heavy machinery products and their development that significantly broadens the range of specialised capabilities and expertise required. To keep up with the rapid pace of change, heavy machinery companies are implementing parallel organisational, technological, and innovation process changes.

The design process for complex engineering products demands expertise from multidisciplinary teams that include mechanical, manufacturing, software, and automation engineers (Kurvinen *et al.*, 2021a). Schools teach engineering disciplines separately, and challenges arise in the workplace when graduate engineers are asked to work together on a multidisciplinary team (Van den Beemt *et al.*, 2020). A matrix organisation is increasingly used to provide inter- and cross-disciplinary expertise and focus talent on a specific application or area. Although working in a matrix organisation can enable improved cooperation, discussion, and personal efficiency, it also places emphasis on the manager and inhibits free individual contribution (Lukinaité & Sondaité, 2017).

In high-end technology products, making efficient use of a matrix organisation requires a high level of both managerial skill and experience. Management competence has a direct effect on team competence (Radujković & Sjekavica, 2017). Commonly, companies address the coordination of multidisciplinary team efforts by having senior engineers guide junior engineers to ensure they cover specific application demands and aspects that are important from a design perspective. However, this approach has limitations when the multidisciplinary aspects are broader and more interconnected, *e.g.*, when dealing with software intensive products or when adding complex new features, such as computational vision (Timperi *et al.*, 2021).

As the expertise required for new product development has quickly broadened and diversified well beyond existing competence levels, the manufacturing industry has restructured around business and innovation ecosystems. Within these ecosystems, organisations apply open and collaborative innovation practices, such as cooperative development approaches, to facilitate ecosystem-level research and development (Urbinati *et al.*, 2020). Digital twins are one of a number of current technologies that assist the co-development process of machines and equipment. These processes are designed to refocus research and development more directly onto industrial needs while engaging other relevant stakeholders, like customers and suppliers, in the development.

Although digital twinning promises to significantly enhance co-development (Onaji *et al.*, 2022; Wang and Wang, 2019), relatively few studies have been published from this perspective. Particular consideration should be admitted to if co-development with digital twins can offer remarkable business value with respect to traditional digital product development processes. More research is needed into better focusing research and development on industrial needs while engaging other relevant stakeholders in the development cooperation. The case study presented a paradigm shift from the traditional product design process, where product designers and engineers work in matrix organisation and collaborate with the best practices inside companies, to a new operating model where simulation methodology is available at all stages for all parties involved in the design and manufacturing of the product.

2 Related work

2.1 Digital twin business ecosystems

A digital twin implemented across an organisation offers internal (and external) stakeholders a variety of tools to increase knowledge capture and availability (Silva *et al*., 2021). Being more than a storage for resources, it relates rather on the interaction and acquisition of information in the spirit of a sharing platform (Tao *et al*., 2020). Parmar *et al*. (2020) considers an organisational digital twin as a combination of data flows from various organisational aspects like people, assets, and activities that helps to achieve a holistic, virtual reflection of an organisation – a living simulation of its real counterpart. They can be used for improving business processes, decision processes, the understanding of customer behaviour, and new product development.

There are also examples of digital twins promoting inter-organisational collaboration (Wang and Wang, 2019). From this viewpoint, the digital twin platform will make fresh value propositions possible and enable the construction of new business models that can result in concessions in lead time and cost, refine design by proving that expectations and requirements are met, enhance knowledge sharing and capture, and eventually, incorporate extra value to the offering, which will improve product offering (Silva *et al*., 2021).

These highlight the importance of building an ecosystem around the digital twin. Digital twins unite obtainable information with digital artifacts, models, and data (Rosen *et al*., 2019). Effective use of digital twins necessites that the different internal and external stakeholders utilising digital twins distribute information with each other (Kokkonen *et al*., 2023). This collaboration has the nature of a digital ecosystem because it is formed by organisations and humans sharing digital models and artifacts via platforms (Rosen *et al*., 2019).

Tao *et al*. (2019) argued that minor emphasis has been put into probing the appropriateness of digital twinning for design of a product. Especially, the extent to which and how the synergy, communication, and coevolution betwixt a physical entity and accompanying digital version result the design process as more instructed, precipitated, and innovative. They state that physical entities can be transformed into more 'intelligent' to rectify real-time behaviours based on 'piece of advice' suggested by the virtual entity. And the virtual entity may be transformed extra 'factual' to precisely project the real-world situation of the physical entity.

2.2 Managing the co-development

A primary aim of digital twin ecosystems is to transfer digital objects dynamically to enable the co-creation of inter-organisational value (Rosen *et al*., 2019). An ecosystem formed around digital twin is not merely a digital platform for the exchange of knowledge and information. It is "a socio-technical network of humans and organisations working collaboratively around digital twin technologies to co-create value" (Kokkonen *et al*., 2023). Rong *et al*. (2015) defined the following dimensions of an Internet of Things -based ecosystem: the organisation that provides the digital platform, the offering round which the ecosystem is constructed, and the variety of partners attaining benefits by operating in the ecosystem. Alike, a digital twin ecosystem is a complicated entity that contains distinct partners taking part to co-development via the digital twin platform.

The key to implementing a digital twin ecosystem is adopting a socio-technical view that allows for different internal and external stakeholders to collaborate in a wide array of processes from product development to decision making (Silva *et al*., 2021). This requires, for example, technical receptivity to the digital twin platform, objectives agreed upon among the different stakeholders, and a solid customer-centric stance (Kokkonen *et al.*, 2023). But at its best, the ecosystem approach assists in combining the profusion of information and the produced knowledge in a surrounding that can be leveraged to improve the efficiency and costs of the product offering (Silva *et al.*, 2021).

Physics-based simulation that is capable of real-time calculation is attractive as the main platform. In the product design phase, different research disciplines can be benchmarked, verified, and further tested. By developing a product in the virtual world, different configurations can be studied more broadly and methodologies can be developed, for example, to optimise communication or develop smart software features or radical innovations related to the product and its software.

2.3 The potential of real-time simulation

Real-time simulation has proven to be an effective tool that is being implemented increasingly in machine development (Saunila *et al*. 2021). Understanding how a machine's dynamic behaviour is affected by variations in the design variables is critical, and a good computer simulation model can provide this understanding (Kurvinen *et al*. 2020). Several approaches to solving machine dynamics have been described in the literature, and increases in computing capacity are making it plausible to resolve solutions that determine big and complex systems including realistic mechanic features, such as mutual clearance and big deformation. Physics-based simulation ensures that real-world boundary conditions are included in the simulation model, therefore ensuring that simulated behaviours are realistic. From the application perspective, computationally efficient and accurate real-time models are particularly desirable. Velocities and accelerations can be determined by directly measuring displacements. But with physics-based simulation, these can be converted to more usable information, such as the forces being produced within the virtual structure.

In heavy machinery, system dynamics are typically important. Therefore, the manufacturers of heavy machinery already have the good internal capability to calculate the dynamics of their systems (Mohammadi *et al*., 2020). Changes in dynamics can reveal *e.g*., vibration issues (Blundell & Harty, 2015).

Multibody system dynamics is often applied to model these kinds of complex systems. They can be modelled directly while still capturing behaviours both accurately and with computational efficiency. The multibody system dynamics methodology is specifically usable when big displacements or rotation happen, and when different bodies are interlinked with joints. In applications where low frequency vibrations occur, the approach can be used to accurately capture dynamic behaviour (Shabana, 2020).

Because of the insights provided by multibody system dynamics simulation, product behaviours can be assessed with good accuracy in the product design phase (Alaei *et al*., 2018). This is especially important for the design of complex products, a highly iterative exercise (Kurvinen *et al*. 2021a; Uzhegov *et al*., 2015). For example, given an accurate and computationally efficient simulation model that can operate in real time, initial control system design can be carried out in the virtual environment (Hannola *et al*., 2021).

To streamline the process, virtual product representations can be simplified and divided into smaller pieces. This is referred to as surrogate modelling, and it makes it easier to focus only on the most relevant data. With surrogate modelling, the design process can be opened to involve outside players, such as subcontractors. The focused simulations make it easier to visualise aspects of the coming product and to narrow the focus of the development team to the most relevant tasks (Kurvinen *et al*., 2021b). This, in turn, enables more effective use of higher-skill -level personnel and the subcontractors, in parallel modular innovations because the requirements and tasks are explicitly requested and controlled with respect to the overall system (Xu *et al.*, 2021). As a summary, in the recent years the real-time simulation methodologies have developed significantly and can provide the technological approach to simulate complex systems. Table 1 presents the compilation of existing research and gaps in the current understanding that have informed the objective of the study.

Table 1. Summary of the related works

Research stream	**Key takeaways from the perspective of current research**	**Research gap**	**Research objective**
Digital twin business ecosystems	Includes the interaction and sharing of information (Kokkonen et al., 2023; Parmar *et al.*, 2020; Silva *et al.*, 2021; Tao *et al.*, 2020). Promotes inter-organisational collaboration that can result in concessions in lead time and cost, refine design by proving that expectations and requirements are met, enhance knowledge sharing and capture (Silva *et al.*, 2021; Wang and Wang, 2019).	How the synergy, communication, and coevolution betwixt a physical and digital realm facilitate the product design process?	Propose a methodology for co-development in digital twin business ecosystems: • An interface or model which is up-to-date available to all stakeholders during the process. • Utilising computationally efficient and accurate real-time simulation methodology as the main digital model approach.
Managing co-development	Requires a socio-technical view that allows for distinct stakeholders to cooperate in a variety of processes from product development to decision making (Kokkonen et al., 2023; Silva et al., 2021).	How different research disciplines can be benchmarked, verified, and further tested? What methodologies allow different configurations to be studied more broadly and to optimise communication?	
Real-time simulation	Ensures that real-world boundary conditions are included in the simulation model ensuring realistic simulated behaviours (Blundell & Harty, 2015; Kurvinen et al. 2020; Mohammadi et al., 2020) Product behaviours can be assessed with good accuracy in the product design phase (Alaei *et al.*, 2018; Hannola *et al.*, 2021; Kurvinen et al. 2021a; Uzhegov *et al.*, 2015). The design process can be opened to involve variety of parties enabling more effective use of higher-skill-levels in parallel modular innovations (Kurvinen *et al.*, 2021b; Xu *et al.*, 2021).	What approach assists to resolve solutions that determine big and complex systems including realistic mechanic features, such as big deformation?	

3 Case study: Panel repair line

The example case in this study concerns a panel repair line from the plywood industry. This industry was selected due to its challenging nature and the need for specialized expertise. Plywood is an engineered wood comprised of cross-laminated veneer sheets bound together with an adhesive to make a panel. Manufactured from several different hardwood and softwood species; the most common are birch, poplar, spruce, fir, and southern yellow pine plywoods. There are a number of standard panel sizes. However, the lengths, widths, and thicknesses vary depending on end use case and the variability of the raw materials used.

The exact composition of the end product is affected by market needs and raw material availability. For example, the lengths and qualities of log available from the forest near the mill will influence composition. With length and width normally expressed in imperial units, the most common outer dimensions of plywood panels vary from 4 x 4 ft to 8 x 8 ft or to 5 x 12 ft (one foot = 30.48 cm). Thicknesses vary between 4 and 50 mm.

Part of the overall plywood manufacturing process, the panel repair line performs one of the final operations. It repairs surface defects in the assembled panels (Raute, 2022). Commonly occurring defects include knot holes, pitch pockets, or cracks in the surface veneer. Each of these are repaired with end-product-specific one- or two-component fillers. For some defects, such as pitch pockets, routing (milling) is done to remove pitch or other undesirable materials before adding a filler material. Figure 1 depicts a typical panel repair line.

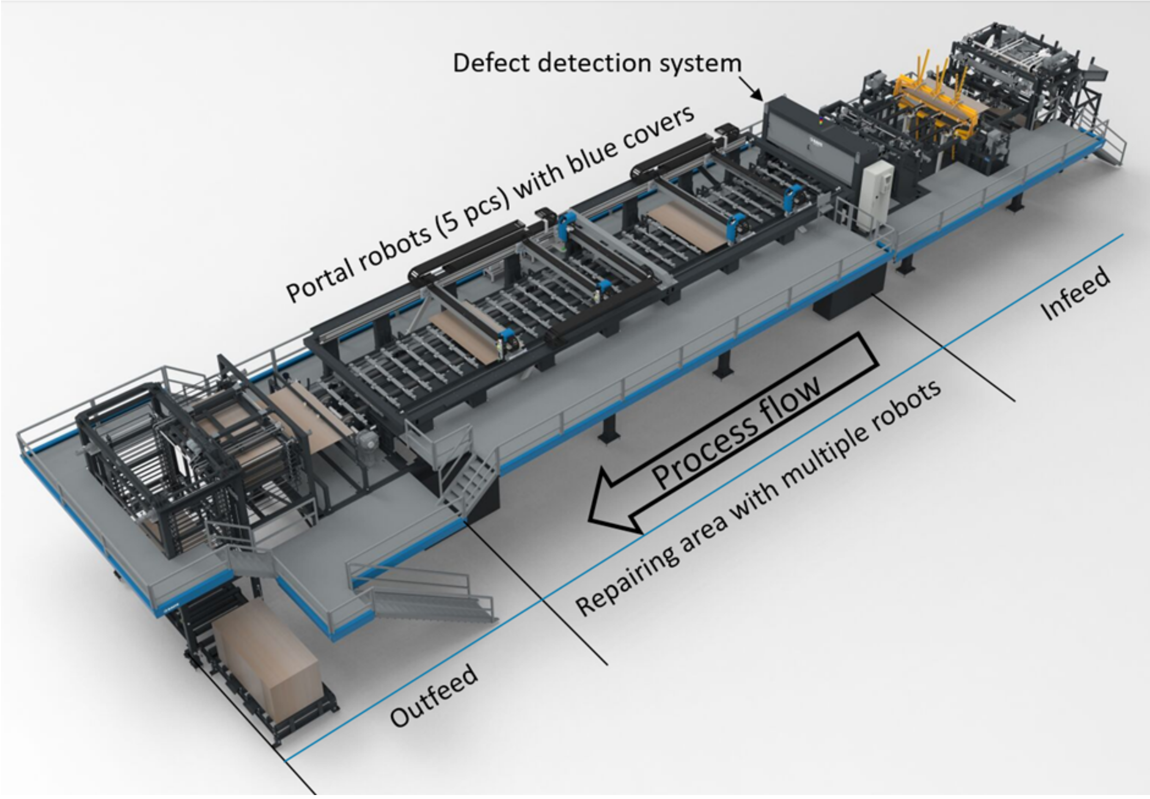

Figure 1. Panel repair line R7

3.1 Coordination challenge

The panel repair line includes several operations that can be classified into four distinct functional groups: infeed, defect detection (with cameras), repair (with portal robots), and outfeed. A vacuum conveyor moves the infeed panels past a defect detection camera, which records the coordinates of all defects for each panel in a panel-specific coordinate system. Next, the panels are conveyed to the repair area where portal robots repair defects according to the defect information gathered by defect detection system and the recipe rules used.

The number of portal robots varies according to required end product capacity and quality. The number needed is also affected by the quality of the raw material or surface veneers. The number of defects that must be repaired varies in amount, location, and size between individual panels and between production batches. So, the production line must be flexible to optimise production over the range of conditions.

A multidisciplinary engineering team with mechanical, automation, process engineering, and machine vision skills is required to design an effective panel repair line. Throughout the design process, effective and well-timed communication among members of the team is essential to achieving rapid design iteration. The appropriate application of digitalisation is one proven approach to achieving this necessary communication, and for this case example, a digital twin was developed for the three most critical elements of the panel repair line: the vacuum conveyor, the defect detection system, and the (portal robot) repair area.

3.2 Solution complexity & interconnectivity

Because it must move the panels reliably and accurately from the beginning of the repair process to the end, the *vacuum conveyor* is crucial. The smallest defects needing repair might be cracks that are only a few tenths of a millimeter wide. How precisely a panel maintains its relative position determines the quality of these repairs. Vacuum conveyor speed is adjusted to optimise throughput while still ensuring that all panel defects will be properly repaired.

The *defect detection* system must quickly and accurately define and store coordinates for all visible defects so that the portal robots of the next operation can immediately begin making repairs.

In the *repair area*, several portal robots act together in cooperation to repair panel surfaces. Commonly, the robots are divided into subgroups, each equipped with different tools. A common grouping for five robot systems includes two robots with routers (milling heads), a robot with a one-component filler tool, and two robots with two-component filler tools. Precision mechanical components are used for the robots with top-quality linear motors and guides and with weight optimised portal beam structures.

Because of the natural diversity of defects and the variability of their location on the plywood panel and because they must often share the same working space, coordinating the movement of the repair robots can be challenging. The control system must be capable of adapting to dynamic changes to keep up optimal process flow in all situations.

3.3 Data and software intensiveness

Solving the needs of control system development was a primary aim of the digital twin development effort. Figure 2 shows the schematic structure of the resulting digital twin.

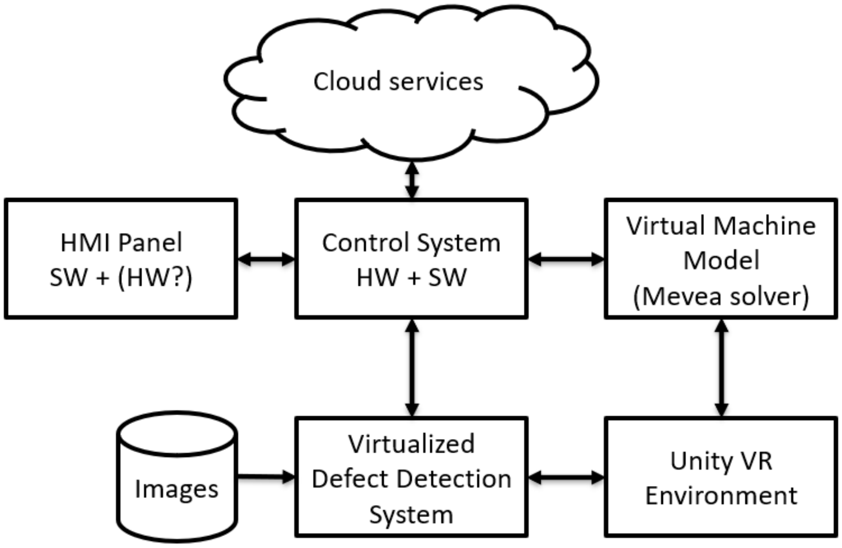

Figure 2. Schematic structure of developed digital twin

Camera images coming from the panel repair line feed into a virtualised defect detection system in the digital twin, which runs as a virtual machine. Output from the virtualised detection system is sent to the Unity Virtual Reality environment (a commercial software product) and the hardware- and software-based control system. Control system software defines appropriate actions according to information gathered and sends messages to the virtual machine model, which then solves for machine dynamics and sends feedback to the control system. This is done in real time for each time step. The control system hardware interfaces with the virtualised camera, the virtual machine model, the Human Machine Interface panel, and cloud services. The entire process is visualised in the Unity Virtual Reality platform.

3.4 Reflections on the approach

The case study presented a paradigm shift from the traditional product design process, where product designers and engineers work in matrix organisation and collaborate with the best practices inside companies, to a new operating model where simulation methodology is available at all stages for all parties involved in the design and manufacturing of the product. Previously, the product was designed by taking account the mechanics and automation included. Meaning that prior to applying the simulation methodology, the product design and delivery process was done as a chain from product design, manufacturing to delivery. For example, different functionalities of the product, such as mechanics, automation, and machine vision, were previously briefly tested by the producer and finalised when implemented in the customer premises. When machine vision is implemented in the product and the challenges it causes is tested not until in the final product, it results in significant delays in the supply time of the product. The applied simulation methodology, the digital twin, was designed to significantly enhance the co-development of the product. This resulted that the product development could be made at several locations with different internal and external parties. The proposed methodology allowed testing the different functionalities prior to implementation in customer premises. After testing with the help of a digital twin, the product was more ready when delivered to the customer; the product was a finished immediately at commissioning. This is because all the necessary functionalities could be tested beforehand; even the ones that could not have dared to test on a physical machine. In this way, the finishing could be done without causing any delays to the customer. For example, including machine vision in the product brought challenges to the process (as conducted separately from basic product development). Simulation methodology assisted in overcoming the challenges as the producer could see how the different functionalities work together. When the simulation methodology allowed correct automation codes running already in the testing phase, user interfaces, digital service data collection and reporting could be done in advance, facilitating on-time feedback on the development. As a result, the final product was more ready when implemented into the customer premises. This reduced the finalisation time after implementation which significantly reduced the entire supply time of the product. Thus, adjusting machine vision during the manufacturing of the product will fasten the supply time significantly.

4 Conclusions

A methodology for constructing a co-development platform was explored in this research, and an industrial case featuring precision dynamics and high mechanical complexity (the panel repair line) was used as an example. The repair line system was augmented to make effective use of a *virtual camera*. The proposed approach supports a development environment that makes it possible to educate and train design experts in working with a multidisciplinary and iterative process as product complexity increases. The improved development environment also makes it possible to transform product offerings to be more software intensive, which enables maximising performance and delivering on customer requirements at an optimal level.

The key takeaways of the research are the following.

- Co-development in a digital twin business ecosystem leads to (1) *coordination challenges* that are only exacerbated in the case of external collaboration, (2) *complexity and interconnectedness challenges* for developed systems, and (3) enhanced *data and software* *intensiveness challenges* in machine building that disturb management routines and challenge technical standards.

- These challenges can be addressed with (1) *digital twin data management* that combines disparate data types, (2) s*urrogate models* that quickly provide relevant information to relevant persons by developing and codifying interfaces, and (3) *virtual (software*) *prototyping* that enables rapid low-cost iteration of software variants, free from the slower pace of hardware revision.
- Co-development in a digital twin business ecosystem makes it possible to transform rigid business control mechanisms, enabling more informal controls that promote initiative and creativity from development personnel. When all relevant information and communication is available to those who need it, informal procedures and policies emerge that effectively take things forward and break hierarchical power relationships. The need to construct formal control mechanisms that inhibit co-development can be reduced.
- The proposed digital twin methodology enables (1) *faster control system* programming, *i.e.*, *in situ cooperative testing* of all key elements of the repair line, (2) *testing of Human Machine Interface panel programs and data gathering and cloud services* early in the product development process, (3) *better cooperation* between development group teams by enabling "co-testing" and serving as a common development platform, (4) a better understanding of system operation to *focus individual actions* on issues relevant to the performance of the entire system, (5) a *faster and more reliable product development cycle*, *i.e.*, a shorter path to profit for a new product offering, and (6) *inexpensive faster-than-real-time operation* that makes it possible to explore different production line setups to address specific customer needs.

The case study used for this research was development of a plywood panel repair line, a system that features precision dynamics and high mechanical complexity. It is a high-end product tailored to specific customer needs. As a result, panel repair lines are manufactured in low production volumes and subject to significant variation from order to order. The methodology developed here represents an excellent vehicle for future studies of other unique repair line configurations. The methodology used can also be applied in other industries for products featuring precision dynamics and mechanical complexity. For example, both stationary and mobile machinery share the same challenges in the control of the highly dynamic applications and optimisation of the sustainability, efficiency, and productivity. Moreover, it would be equally interesting to study the extent to which and in what context real-time virtual product simulation can enable more effective investigation of new product software developments. This type of future research could allow extending the technology further to new uses, such as planning fleet level operation, optimisation and factory and process level semi-automatic control. Additionally, future research could explore the relationship between the proposed case model and AI, specifically examining how AI and other emerging technologies influence the evolution of such models.

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