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ABSTRACT

In mechatronic machine design and development, it is no longer enough to think about machine functionality and integration as machines are increasingly digitalized. Virtual upgrades are being made to manufacturing systems to keep up with the need for faster product cycles, higher quality, and the introduction of Industry 4.0 technologies. The design and development of new mechatronic discrete manufacturing machines (MDMM) should thus include these characteristics in their design. However, most machine builders do not have the capabilities and resources to do virtual engineering (VE) at the required level, which means these machines are made with limitations or sometimes without their virtual counterparts. Reusable VE MDMM modularization allows machine builders to obtain these competencies quickly and with fewer resources. This research proposes developing adaptable digital twins (DT) by modularizing all virtual and physical mechatronic machine aspects. DTs are well-explored in literature, but re-engineering them requires massive resources and is often unviable. We introduce a new DT-based approach that allows machine builders to quickly re-engineer, adapt, and test machines, given its modular confined approach. Although VE on different abstraction levels still must be developed, confined modularization allows hiding the complexity into modules rather than addressing the entire machine simultaneously. Building machines through modularization is thus an investment, as machine builders and other stakeholders will be able to use and reuse them later for other machines, reducing the overall resources that go into the development. The paper shows how to develop adaptable DT machines using Siemens tools related to virtual engineering.

1. Introduction

Virtual Engineering (VE) tools are available for all aspects of the design and development of machines, witnessed both in the shared amount of different tools and in the standards upon which they are built (Hankel and Rexroth, 2015; Bangemann et al., 2016). In this context, there is a continuous discussion on how to develop smart, intelligent machines that can interact and adapt to the factory of the future, characterized as both adaptable, autonomous, and context-aware (Cruz Salazar et al., 2019; Hribernik et al., 2021). Currently, state-of-the-art machines can communicate in real-time with other assets while forecasting and adjusting to new scenarios without significant machine interruptions (Hribernik et al., 2021).

Reconfigurable Manufacturing Systems (RMS) have long been anticipated as a promising technological solution to tackle continuous changes but have so far been missing practical examples of applying it in commercial manufacturing, according to (Morgan et al., 2021). Therefore, a promising way of developing RMS towards commercial manufacturing is to use Module-Based Machinery Design (MBMD), in which machines are divided into Modular Machine Families (MMF) based on platform-based development (Gauss et al., 2019; Jiao and Tseng, 1999).

The challenge in a mechatronic discrete manufacturing machine (MDMM) context is to create a consistent development environment that includes all aspects of the product life cycle, going from plan/design, build, operate, to maintain (Konstantinov et al., 2023; Harper et al., 2019). In an Industry 4.0 (I4.0) context, these machines compose a cyber-physical production system (CPPS), enabling the development of virtual machine aspects and digital twin competencies. As previously investigated in (Konstantinov et al., 2023; Hansen et al., 2022), no individual tools can develop and support a complete digital twin machine through all its lifecycle phases; it is rather handled as an interlacing of several digital tools. In this context, tools that facilitate all the lifecycle phases are sought for (Konstantinov et al., 2023).

The scientific contribution of this research is thus on creating a framework that supports the development of agile digital machine

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development throughout all the development phases relating to its lifecycle.

Specifically for MDMM development, this is a challenge since these machines traditionally consist of different engineering elements, such as mechanical, electrical, and automation elements, at different abstraction levels (Gauss et al., 2019; Hansen et al., 2022; de de de Oliveira Hansen et al., 2021). At the same time, the DT of mechatronic manufacturing systems also includes the connectivity between the virtual and physical machines, using data to add predictability to the equation (Zheng et al., 2022). In a broader context, the individual DT mechatronic machine could be put in context to other machines within a factory and, e.g., adapt towards load, energy efficiency, forecast, and stock (Zheng et al., 2022). The development of virtual MDMM, which incorporates these elements into their design, is thus getting evermore complex.

Machine builders, particularly SMEs, do not have the resources and competencies to commence DT development (Masood and Sonntag, 2020). Therefore, users of the machines (end-users) are missing out on many of the benefits they could have had, such as increased productivity and higher production efficiency (Leurent and Boer, 2019). End-users are consequently enforcing their requirements towards the machine builders, creating bottlenecks as they are not ready for the transition. Currently, end-users have started to develop their own virtual competencies. However, this will not solve the need for upskilling at the machine builders (Grube Hansen et al., 2017). Hence, the research points towards creating VE adaptable MDMM throughout all the development phases towards the DT stage.

In VE, there is a close correlation between the perceived value of a virtual model and the time it takes to develop it (McGregor, 2002; Noga et al., 2022). In this process, the perceived value of the virtual model is highest in the early phases, while the models' confidence and cost are still low. However, once the costs of the model become higher than their perceived value, it takes a sharp drop (Noga et al., 2022). Costs, hence, must be kept low in relation to their value. Once a machine has been developed, much focus is channeled toward the physical systems rather than their virtual counterparts (Tao et al., 2018). However, keeping virtual models updated enables testing and verifying new machine scenarios before implementation. However, retrofitting old machines to new standards and conditions sometimes exceeds the costs and efforts of developing the original machine (Jaspert et al., 2021). Thus, starting with an adaptable and agile foundation, higher flexibility and reconfigurability can be built into the physical and virtual modules from day one. For such, both the physical and the virtual machine must be designed towards adaptable solutions to stay agile, enabling quick adjustments to sudden changes. Here, modularization saves significant time and costs, as only limited efforts are required to develop and test new machine configurations (Obst et al., 2015).

Developing a MDMM with DT competencies is getting increasingly complex while the variation of virtual tools keeps increasing (Bi et al., 2022). Modularizing every part of the machine development significantly reduces the time and effort needed to develop these machines, making changes and variations faster. However, cohesion or openness between the digital tools is required to make it possible (Zheng et al., 2022; Lin et al., 2021; Koren and Shpitalni, 2010).

In this paper, we propose how to develop adaptable MDMM with DT competencies, using dedicated and coherent VE tools for the development, in which every part of the machines has been modularized based on the functional requirements (FR) for adaptability.

As digital twins have been the subject of extensive research, the value of this study lies in two key aspects. First, we show how to integrate and use VE tools that support the complete development of all phases related to DT MDMM in a practical case. Secondly, we show how to extend this knowledge towards an adaptable DT machine setup through modularization and reconfigurability, which can help SMEs overcome the challenges related to VE time and complexity.

The remainder of the paper is structured as follows. Section 2 presents the theoretical background and relevant concepts on adaptable machine development, virtual engineering, and digital twins. Subsequently, Section 3 describes the research design in which we use case-based design and action research to explore how to create an adaptable DT machine in a laboratory setting, while Section 4 shows the results from the case study, where the concepts were successfully implemented at the University of Southern Denmark, motivated by the large Danish manufacturing company, VELUX who specializes and manufacture roof windows, skylights, sun tunnels, and related accessories. Section 5 evaluates and discusses the results and suggests how to optimize the current research further. Section 6 concludes by summarizing the research while pointing out further research opportunities.

2. Related literature

In VE, the technical parts that make up each asset are still highly vendor-specific, adding significant time and cost to the machine development process (Hansen et al., 2022; Konstantinov et al., 2023). Therefore, more pragmatic approaches toward implementing digital tools are needed (Hribernik et al., 2021; Gauss et al., 2019). Here, standards and reference architecture literature can serve as a guide towards the aspects that should be included at each level of the MDMM design and development phases (Harper et al., 2019; van Dinter et al., 2023; Lee et al., 2015) (Konstantinov et al., 2023). describes the standard elements that should be incorporated into a DT. In (Konstantinov et al., 2023), several VE tools were analyzed and compared to a DT use case based on (Konstantinov et al., 2023), which revealed that most tools include features for planning and building the DT, while none of the examined tools addressed DT operation and maintenance. The absence of early design models with DT competencies has also been highlighted by (Jones et al., 2020; Panarotto et al., 2023). Including these features in the design, therefore, seems apparent.

Several VE tools are thus needed to create and operate a DT, meaning most tools are an intertwinement of several tools connected through application programming interfaces (APIs) or Open Platform Communication such as OPC-UA (Zheng et al., 2022; van Dinter et al., 2023; de Oliveira Hansen et al., 2023; Semeraro et al., 2021). This construct adds significant complexity to the development and means corrections, changes, and updates are not automatically implemented, which creates inconsistencies, errors, and redoes throughout the development of a machine (Hansen et al., 2022; Bi et al., 2022; De Oliveira Hansen et al., 2021). Building upon a coherent VE development platform is a prerequisite to avoid these issues if complete openness and coherence cannot be achieved at the needed detail level.

Integrating more functions into fewer DT development platforms might be a solution for more consistent development (Hansen et al., 2022). At the same time, complexity is a matter of reducing the number and types of elements, their interaction, and the dynamic changes and the relation of elements over time (Bi et al., 2022). This could be done by automating redundant development processes, e.g., through automatic code generation based on simulation logic as witnessed in simulation tool vueOne (Jbair et al., 2022) or by modularization (Gauss et al., 2019; Panarotto et al., 2023; Ghobakhloo, 2020; Erixon, 1998).

Simulation is an effective tool to test and perform new experiments before implementation (Renna, 2010). The more experiments and tests that can be done in advance, the more confidence there is in the solution. Meanwhile, the development time of the simulation is directly related to its perceived value (McGregor, 2002; Noga et al., 2022). Using more time on tests and experiments is thus not necessarily generating added value to the solution; it depends on its perceived value. In other words, there is a tradeoff between confidence and perceived value, which is the same throughout all the VE development phases.

Here, pretested simulation modules make arriving at the best solution in the shortest possible time easier and faster. When the machine setup has been decided upon, the machine should be emulated to verify the construct of the machine elements in a close-to-reality environment

(McGregor, 2002). This is followed by virtual commissioning (VC) to verify how the mechanical, electrical, and automation elements behave as a complete machine and if there are discrepancies and errors between them (Leng et al., 2021; Reinhart and Wünsch, 2007).

Ideally, the VE tools should be rooted within the same platform environment and share/reuse information, as the MDMM behavior is the same seen from different engineering silos (Hansen et al., 2022). Once the virtual machine has been developed, the physical machine is built. After that, the virtual and the physical machines can be connected in a bidirectional data communication to form a DT machine to understand, predict, and optimize machine design, configurations, and operations (Lin et al., 2021; Leng et al., 2020; Cimino et al., 2019).

The so-called digital twin is, in other words, the full realization of the MDMM. This construct is valuable to machine builders and end-users as errors and breakdowns can be predicted and avoided (van Dinter et al., 2023). However, these machines are often not designed with this feature, as previously argued (Jones et al., 2020; Panarotto et al., 2023).

Modularization is hence positively related to both short time to market, complexity reduction, and higher quality (Piran et al., 2017). Modularization makes machines more agile and flexible while risks are further reduced (Ghobakhloo, 2020). If developed right, these modules can be used across different levels of the factory (Åkerman et al., 2018), like LEGO bricks, which can be used in many combinations (Marseu et al., 2016). However, modularity has to be built into the machine's design and production to gain the full effect of its advantages (Jones et al., 2020; Panarotto et al., 2023; Kubota et al., 2017). This is far from an easy task as all associated partners and suppliers will have to amid to this and agree on what the modules are supposed to do (aka functional requirements (Gauss et al., 2019); Kubota et al., 2017; Suh, 1999) and how to achieve the expected benefits (aka modularity drivers (Erixon, 1998); Andersen et al., 2022). This leads to a tradeoff between the two. Therefore, some of the FR is likely to be reduced to gain the benefits of modularization.

Moreover, as these machine modules are to be integrated into other machines and parts of the production, they must be designed as reconfigurable manufacturing systems (RMS) (Gauss et al., 2019). Although RMS has for long been seen as the future for manufacturing (Gauss et al., 2019), it has so far been missing practical examples on how to apply it in commercial manufacturing (Morgan et al., 2021), and with good reason, as eight types of characteristics should be included in the design, which is: modularity, integrability, customization, convertibility, scalability, diagnosability, mobility, and adaptability (Morgan et al., 2021; Koren and Shpitalni, 2010). In (Gauss et al., 2019), a practical way of combining RMS and modularization has been proposed, sorting mechanical modules into MMFs. Although this method is far from novel, as seen in (Erixon, 1998) and (Otto et al., 2016) then, the method is highly useful, as also witnessed by (Panarotto et al., 2023). This construct could be extended to include all aspects of the DT development, including electrical and automation aspects, which has also been noted by (Heimicke et al., 2019) and (Panarotto et al., 2023).

The individual module can thus come in different sizes and shapes and thus must be organized into MMFs to maximize its usage and pave the way toward reconfigurability. This method has already been explore in (Jiao and Tseng, 1999; Erixon, 1998) and extended in (Gauss et al., 2019). A module could, therefore, have many links to other design constructs within the same MMF (Gauss et al., 2019; Jiao and Tseng, 1999). While its adaptability is determined by its ability to be responsive to changes (Morgan et al., 2021). The usability of the individual module consequently relies on the level to which the module can be generalized (Andersen et al., 2017). In this context, it is argued that these modules should be viewed as function-carrying units which combined create a product or a machine (Panarotto et al., 2023; Erixon, 1998; Bergsjö et al., 2015). At the same time, more than 80% of the cost associated with the machine can be traced back to the decisions made early in the development process (Gauss et al., 2019).

As mentioned, a tradeoff between the functional requirements and the module drivers (MD), therefore, must be made (Gauss et al., 2019; Erixon, 1998), which is also the case for the type of virtual tools to be used (Konstantinov et al., 2023). This could also be referred to as a "module boundary definition," as described in (Otto et al., 2016), which is an essential step towards identifying the module's ability to be used in different configurations.

These tools should facilitate the development of digital twins on different abstraction levels (Lin et al., 2021; Shao and Helu, 2020). Such a construct is complex as several pieces of information must be integrated and acted upon in real time, adding significant requirements for the tool platform provider (Zheng et al., 2022).

It has been noted that complexity is measured as the level of uncertainty in reaching certain FR (Suh, 1999). Adding several functions into a module is, therefore, difficult (Otto et al., 2016).

Not only do the DT machine modules have to communicate in a bidirectional data flow between the physical and virtual modules (Fuller et al., 2020; Kritzinger et al., 2018), but relevant information must also be selected in advance (Noga et al., 2022; Shao and Helu, 2020). Here, it is essential to choose a technological platform that supports the same syntaxes, protocols, and standards (Zheng et al., 2022). This makes adaptability to changes easier, as VE development, particularly in the later development and test phases related to emulation and VC, is challenging to change, as they require domain-specific tools (Leng et al., 2021; Stark et al., 2017). The DT machine makes it possible to continuously validate its performance and design, given that it has been built ultra-realistic and in high fidelity (Hribernik et al., 2021; van Dinter et al., 2023; Semeraro et al., 2021; Leng et al., 2021; Glaessgen and Stargel, 2012; Zhong et al., 2015; Lützenberger et al., 2016; Klein et al., 2019). Thus, VE should include all elements required to develop and test new machine setups.

Given the complexity required for integrating virtual tools in relation to the development of the modularized DT machine, a coherent VE development platform was considered essential to avoid model conversions and synchronization inconsistencies.

Standardizing the procedure and content needed for creating and implementing them in actual cases was crucial to test its feasibility, as systematic approaches to VE DT MDMM modularization design are missing (Panarotto et al., 2023; Klushin et al., 2018). Therefore, a framework that supports agile DT machine development should be made.

Next, a standardized methodology to develop adaptable DT modules has been proposed to understand better what each module should include to support all levels of VE for the digital twin MDMM.

3. Methodology

Due to limitations in existing research on practical examples that support the development and implementation of adaptable digital twins (Morgan et al., 2021), this research focuses on case-based action research and design science to explore how to create a modular MDMM with reconfigurable DT competencies.

As with (Panarotto et al., 2023), modularization is used as a tool to reach low cost and quick development of products. However, in this case, the focus is on the framework that supports agility in MDMM rather than state-of-the-art development of satellites. This research focuses on creating a framework that can be generally adapted, as seen in Fig. 1, and practically demonstrated, as seen in Fig. 3. Although, in Fig. 3, vendor-specific tools are used, the aspiration towards open generic solutions is intact, although not feasible with the requirements related to high fidelity mechatronic machines as witnessed in the result section. The case is developed on a mechatronic material handling machine for discrete manufacturing consisting of several modules, referred to as MDMM or simply "machine," both in the prior and the latter. This type of machine is associated with up to 70% of the manufacturing costs of a product, according to (Esmaeilian et al., 2016), and therefore has significant optimization potential.

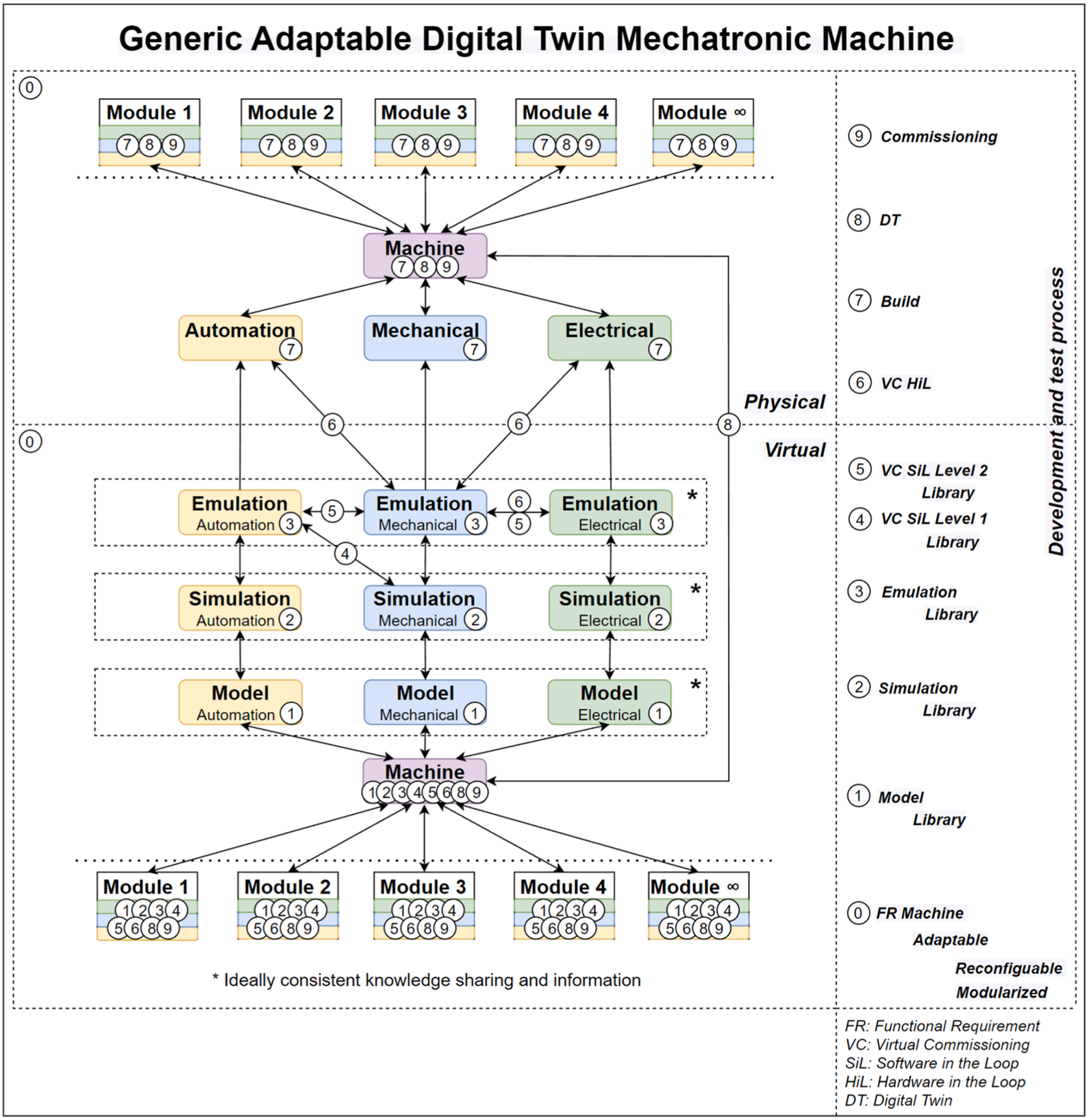

Fig. 1. Generic adaptable digital twin mechatronic machine.

The setup was determined based on the requirement related to a digital twin MDMM setup in relation to the development and implementation phases, as demonstrated in Fig. 1, and with the FR related to adaptability. Fig. 1 shows a generic adaptable digital twin mechatronic discrete manufacturing machine approach that could be used with many VE development tools. The figure depicts the different stages needed to develop an adaptable DT MDMM.

In the lowest part of the figure, VE modules are shown consisting of mechanical (blue), electrical (green), and automation (yellow) elements, indicating that each VE module includes all VE abstraction levels and can therefore work as independent modules without entanglement towards the other modules. Combined, each module makes the VE machine, and within each module, different VE stages are inherent. The VE modules are the very foundation of the VE machine (purple), from which all the physical machine development originates (purple). This is witnessed by the numerical numbers within each element within the figure. Here, Fig. 1 shows a generic adaptable digital twin mechatronic discrete manufacturing machine approach that could be used with many VE development tools. The figure depicts the different stages needed to develop an adaptable DT MDMM. Zero corresponds to the FR rooted in adaptability enabled through reconfigurability and modularization. While one relates to the basic model, e.g., CAD, ladder code, and input/outputs. Number two relates to simulation, where new configurations and designs are explored. Number three, to emulation, which is where the verification of the module is done. In four, the basic VC in software in the loop (SiL) is carried out to validate behavior concerning mechanical and automation elements for validating consistencies between dynamic and logical elements. In some cases, this validation must be extended towards also including electrical elements, such as I/Os and drives, as exact VC is needed in high precision or time-sensitive machine setups. Hence, point number five, indicating and extending VC SiL to a second level, should be included for VE. Number six indicates VC in hardware in the loop (HiL) where real control is tested. Here, the automation code should be downloaded to the physical controllers, while electrical elements should also be included, such as physical drives, motors, and sensors.

The next stage is building the machine physically, indicated as number seven, derived from the VE phase. Once the virtual and physical elements have been created, selected parts of the modules are coupled through an open communication protocol such as OPC-UA or dedicated proprietary communication protocols. Several other communication protocols could also have been used, as seen in (Siemens, 2012, 2022). Once a bidirectional data flow is established, the machine is ready for DT operations, indicated as number eight. As a last part of the tests, a complete machine test is made where everything is tested and stressed to force out potential errors. This part is referred to as commissioning, indicated as number nine. In an adaptable DT machine setup, both the virtual and the physical modules should thus be tested and reconfigured in different combinations in advance. Therefore, the physical modules have been included at the very top of the figure, reflecting the same three engineering elements as the virtual modules, although incorporating only the latter stages of the VE design referring to the VE design in stages five and six.

Between the stages and items within the figure, single or double-pointed arrows combine the different elements. The arrows here show how the individual parts are connected and in which direction the information flows. While the numbers plotted on the arrows indicate the combination of elements.

The above figure should be read from below and up, meaning the foundation of the mechatronic machine is based on the virtual elements. The reusage of VE elements can make development easier, ideally having consistent knowledge and information sharing between the tools, as indicated by the dotted lines surrounding the model, simulation, and emulation phases.

Several requirements go into developing and testing the adaptable DT machine, summarized below, where each encircled number directly relates to the encircled numbers in Fig. 1. On the right-hand side in Fig. 1, the name of the development phase associated with the number is shown, and on the left-hand side, how each development phase is associated with the physical and virtual machine development is displayed. Next, we detail each of them, including the references the model was built upon.

⓪ The FR is aimed toward the adaptable mechatronic machines' ability to be reconfigured into other types of machines within the same MMF, and modularization was, therefore, an essential tool to make this possible (Gauss et al., 2019; Jiao and Tseng, 1999).

Modularization and reconfigurability relate to RMS, which concerns the following criteria: Modularity on both software and hardware, Integrability in component designs, Customization in system capability and flexibility, Convertibility on changeover between existing products, Scalability on the ability to expand overall system capacity, Diagnosability on the ability to identify sources of quality and reliability problems, Mobility on transport mechanisms, Adaptability on ability to be responsive to changes according to (Morgan et al., 2021). Including these RMS characteristics in the design adds complexity to the overall machine, for which modularity should be used to handle it (Cimino et al., 2019; Seidel et al., 2023). Therefore, The machine should be designed as reconfigurable software and hardware modules (Gauss et al., 2019; Shao and Helu, 2020) and in product families from component to system level, including mechanical, communication, and control elements (Koren and Shpitalni, 2010). Here, an open architecture should be sought for to facilitate rapid reconfigurations of the modules (Morgan et al., 2021; Koren and Shpitalni, 2010; Koren et al., 1999). The solution should solve the practical design issues while pointing towards a simplified (Morgan et al., 2021), efficient, and flexible setup for development (Cimino et al., 2019; Seidel et al., 2023).

① The modeling of the machine should be based on a secure platform (Jbair et al., 2022) based on high-fidelity physics-based models (van Dinter et al., 2023; Leng et al., 2021; Kritzinger et al., 2018; Pfrommer et al., 2013; Errandonea et al., 2020; Lu et al., 2020) with the same syntaxes, protocols, and standards (Zheng et al., 2022). Including extension towards PLC integration (Leng et al., 2021; Ovatman et al., 2016) and the possibility of carrying out virtual commissioning (Leng et al., 2021; Liu et al., 2012) with little time discrepancy (Hribernik et al., 2021; Errandonea et al., 2020). It should be possible to extend these models towards a digital twin setup (Zheng et al., 2022; Semeraro et al., 2021; Leng et al., 2021), and the models should assist the machine's physical development (Lützenberger et al., 2016). Furthermore, as the machine should be adaptable, these models have to be reconfigurable (Lin et al., 2021; Leng et al., 2021), easy to develop (Lin et al., 2021) and update (Lin et al., 2021; Derler et al., 2012).

② Simulation is used to explore and test different solutions (McGregor, 2002) both in real-time and faster than real-time (Lin et al., 2021) to arrive at the best solution as quickly as possible (McGregor, 2002). Simulation should be in 3D to be easily understood (McGregor, 2002), and for digital twin machines, preferably multibody dynamic simulation (Konstantinov et al., 2022; Thelen et al., 2022), although coming with high computational costs (Errandonea et al., 2020). Simulation plays an essential role in digital twins (Lin et al., 2021; Yang et al., 2018) and should support real-time synchronization (Lin et al., 2021) needed for virtual commissioning (Leng et al., 2021; Liu et al., 2012; Putman et al., 2017). Moreover, the simulation should be available as a reference model to make efficient commissioning possible (Leng et al., 2021), as well as support decision-making (Lin et al., 2021; Yang et al., 2018) and optimization of the physical machine (Lin et al., 2021; Shen et al., 2020) and the physical layout of a system (McGregor, 2002). It should be easy to build and update and with minimum time and resources (Lin et al., 2021), preferably beyond expert-centric tools (Hribernik et al., 2021; Computing, 2018), and in a cost-effective and flexible environment (McGregor, 2002).

③ Emulation should be used for verifying control systems and procedures risk-free under different loading conditions (McGregor, 2002), describing and predicting the system behavior (Hribernik et al., 2021; Konstantinov et al., 2022), preferably in 3D to understand the behavior (Grube Hansen et al., 2017) more easily. As the system reflects reality, the time is finite (McGregor, 2002) and in real-time (Leng et al., 2021). It is not for experimentation, and repeatability is essential (McGregor, 2002). For emulation, proper tools are needed (Leng et al., 2021; Ovatman et al., 2016), enabling easy usage (Enoiu et al., 2017; Adiego et al., 2015), efficient collaboration in the same environment, reusability and modularity, as well as integration of various PLCs (Leng et al., 2021). During development, protection procedures should be developed (Jbair et al., 2022) and integrated through experience-based design patterns (Cruz Salazar et al., 2019).

④⑤⑥⑨ In virtual/real commissioning, the goal is to validate control and manufacturing activities (Leng et al., 2021; Reinhart and Wünsch, 2007). In real commissioning, the complete machine is tested and reviewed (Reinhart and Wünsch, 2007). Therefore, by increasing the confidence level during VC, more mistakes and errors can be detected in advance (Reinhart and Wünsch, 2007). The VC models should thus be made as high-fidelity models to reduce costs (Leng et al., 2021, 2020) meanwhile having a connection back to the simulation reference models to ensure efficient commissioning (Leng et al., 2021; Reinhart and Wünsch, 2007). It has, therefore, been argued that VC requires domain-specific design tools (Leng et al., 2021; Stark et al., 2017). As much effort is put into the development of VC models, these models should be reusable to reduce costs (Gauss et al., 2019; Marseu et al., 2016) and foster collaboration (Leng et al., 2021; Liu et al., 2012) to validate the codes and the simulation (Leng et al., 2021; Liu et al., 2012).

⑦ During the build and assembly of the physical machine, a realistic virtual representation of the machine will benefit its creation (Hribernik et al., 2021), while a clear design pattern based on prior experience will create common solutions (Cruz Salazar et al., 2019) and thereby make the build, assembly, and updates efficient, which should be strived for (Lin et al., 2021). Moreover, the machine components should facilitate predictability and serviceability (Zheng et al., 2022) with real-time response from and to the components (Lin et al., 2021). Also, ergonomics, safety, and cycle time should be calculated beforehand during the virtual development (Konstantinov et al., 2022).

⑧ The digital twin machine has a real-time bidirectional data communication (Cimino et al., 2019) connecting the virtual and real world through a continuous interaction (Zheng et al., 2022; Semeraro et al., 2021; Leng et al., 2021; Glaessgen and Stargel, 2012). The virtual machine should reflect the physical machine (Jbair et al., 2022), meaning the virtual machine should be ultra-realistic and high-fidelity (van Dinter et al., 2023; Semeraro et al., 2021; Glaessgen and Stargel, 2012), being both adaptive, physics-based, and continuously updated with a link to its reference models to make modifications and optimizations possible (Hribernik et al., 2021; Tao et al., 2019). This will make it possible to continuously validate the performance of a given design (Hribernik et al., 2021; Leng et al., 2021; Zhong et al., 2015; Lützenberger et al., 2016; Klein et al., 2019), but due to the high computational requirement (Errandonea et al., 2020), only relevant data should be used (Shao and Helu, 2020). This also means the complete DT machine model should consist of multiple subsystems with their own DT models, preferably integrating different semantics and syntaxes (Zheng et al., 2022). While running the digital twin machine should facilitate decision-making (Lin et al., 2021) and support different operation stages (Lin et al., 2021; Leng et al., 2020) in real time (Lin et al., 2021; Löfgren and Tillman, 2011). However, real demonstration cases are needed with real reconfigurable digital twin components (Shao and Helu, 2020).

4. Results

During visits to the large discrete manufacturing company VELUX, a close partner within the Manufacturing Academy of Denmark (MADE) that specializes and manufactures roof windows, skylights, sun tunnels, and related accessories, physical machine modularization was witnessed throughout many of the machines within the factory, as seen on the example below in Fig. 2. In the example, design modules were replicated throughout the machine. However, as many of their machines were developed by external machine builders, few of them came with complete virtual counterparts and, therefore, needed to be reengineered towards the required VE level.

Our research and development were therefore triggered towards creating a complete and standardized approach to adaptable DT mechatronic machine development to fill the current gaps in industry and research within the field.

The Siemens software platform was chosen based on the methodology and the required elements, which should go into each adaptable VE DT machine development element. Other VE platforms lacked complete and coherent VE design and development tools that could sufficiently integrate all DT development aspects.

Although, as previously seen in (Konstantinov et al., 2023; Hansen et al., 2022), the Siemens VE tools are far from perfect, requiring much engineering effort and coupling between the highly segmented engineering silos. Despite the lack of reusable information between the highly expert-centric and domain-related tools related to mechanical, electrical, and automation, each of them was able to connect through APIs and with great precision and detail level, creating a continuous development platform in which domain-specific models could be extended towards simulation, emulation, and VC models without changing the platform or file format, effectively having a complete VE development system as seen in Fig. 3 below, which is an adaptation of Fig. 1 but includes the software and hardware utilized to achieve the setup.

The many stages and tools needed to develop a DT machine with the Siemens toolset add complexity to the setup, as domain-specific knowledge would have to be generated for each of the specific VE tools, as previously highlighted by (Hansen et al., 2022). Thus, to handle the perceived complexity, modularization should be integrated into the VE machine elements (Cimino et al., 2019; Seidel et al., 2023). During the investigation, the tools were tested for their functional support towards modularization.

However, as a first step, the FR of the machine and the individual modules were created, inspired by the methods used in (Gauss et al., 2019; Jiao and Tseng, 1999; Panarotto et al., 2023; Erixon, 1998; Pahl et al., 2007; Suh, 1998; Tsukune et al., 1993). The method by (Gauss et al., 2019) has been built upon existing and more established literature by (Jiao and Tseng, 1999; Pahl et al., 2007; Suh, 1998), which relates to FR in modularization. The same structure was used to create Fig. 4 below. This paper does not try to extend modularization concepts or theory but instead uses the methods to expand machine agility in connection with VE development of adaptable DT mechatronic machines. Hence, the focus was on creating modules that would support the overall goal of adaptability. As both modularization and adaptability are part of the requirements related to RMS, these requirements have been adapted towards the FR of the machine to obtain complete adaptability of the modularized machine, as seen in Fig. 4. In this figure, the overall functional requirement has been depicted as FR0 adaptable digital twin machine. It has been built upon the requirements from the literature on reconfigurability and modularization, summarized within the points FR0.1 to FR0.13. From these, constraints were added, selecting three types of technology objects (FR2-FR4) and a common foundation (FR1). While more engineering-specific requirements could be derived from them relating to FR1.1-FR4.1.

A digital twin machine demonstrator for sorting plastic boxes was developed at the University of Southern Denmark to showcase adaptability between modules and technology objects. Based on the VE models, a common foundation was developed based on Bosch Rexroth aluminum profile with a common footprint (FR1). While three types of technology objects were implemented. Two gravity-based conveyor systems to showcase the worth of gravity base multibody dynamic

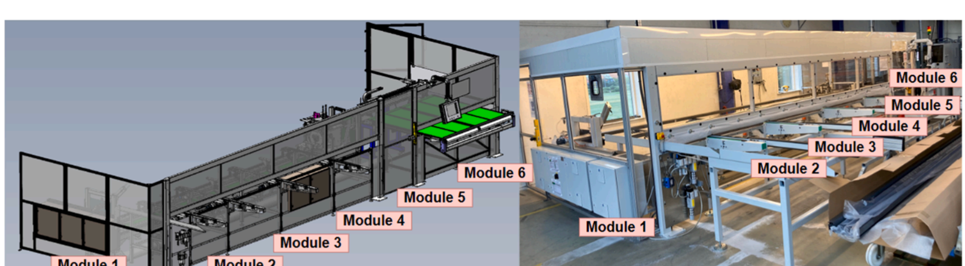

Fig. 2. Example of a modularized machine at VELUX.

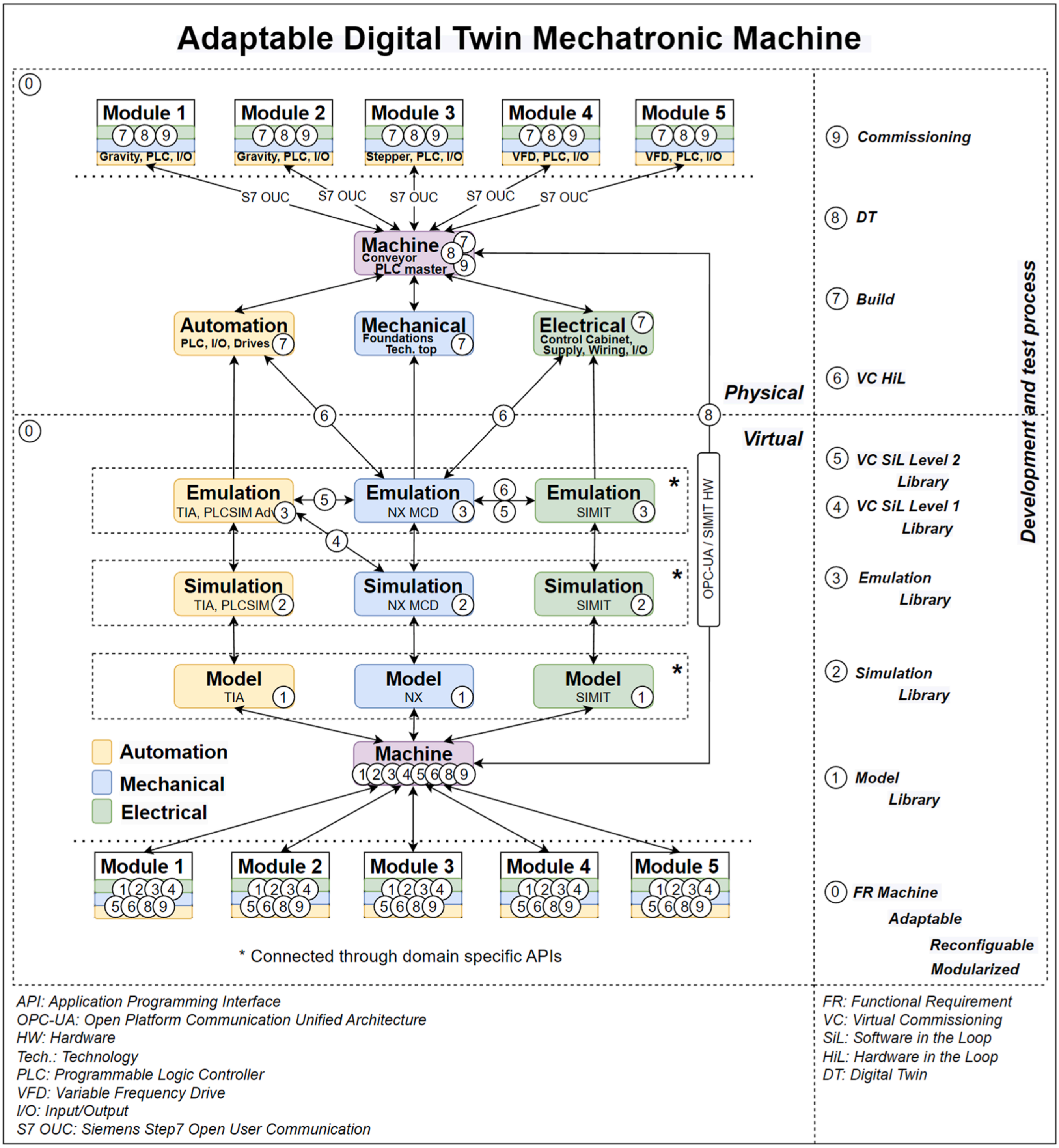

Fig. 3. Framework for developing adaptable digital twin mechatronic machines.

simulations (FR2). A Festo slider powered by a stepper motor to sort boxes was chosen because of its broad implementation abilities (FR3) and two conveyors driven through variable frequency drives with a regular three-phase AC motor (FR4). In broad, a simple setup which allowed for the exploration of adaptability on a practical digital twin setup, as seen in Figs. 4 and 5. In the figure below, the adaptable DT mechatronic machine is portrayed as both a virtual machine and a physical machine, showing each module and the common foundation upon which they are built.

Once the FR had been narrowed down to more engineering-specific requirements according to (Gauss et al., 2019; Jiao and Tseng, 1999; Suh, 1998), then they were clustered as in (Gauss et al., 2019) although simplified, whereupon Design Patterns (DP) were created, scored, and selected according to (Gauss et al., 2019; Jiao and Tseng, 1999; Erixon, 1998; Suh, 1998; Brunoe et al., 2021) whereupon the Design Modules (DM) could be created according to (Gauss et al., 2019; Jiao and Tseng, 1999; Pahl et al., 2007; Suh, 1998; Tsukune et al., 1993), see Fig. 6.

The modules were thus designed as open and integrative, to be used in different combinations to increase reusability and exchange of the designed modules and components, although contained towards the

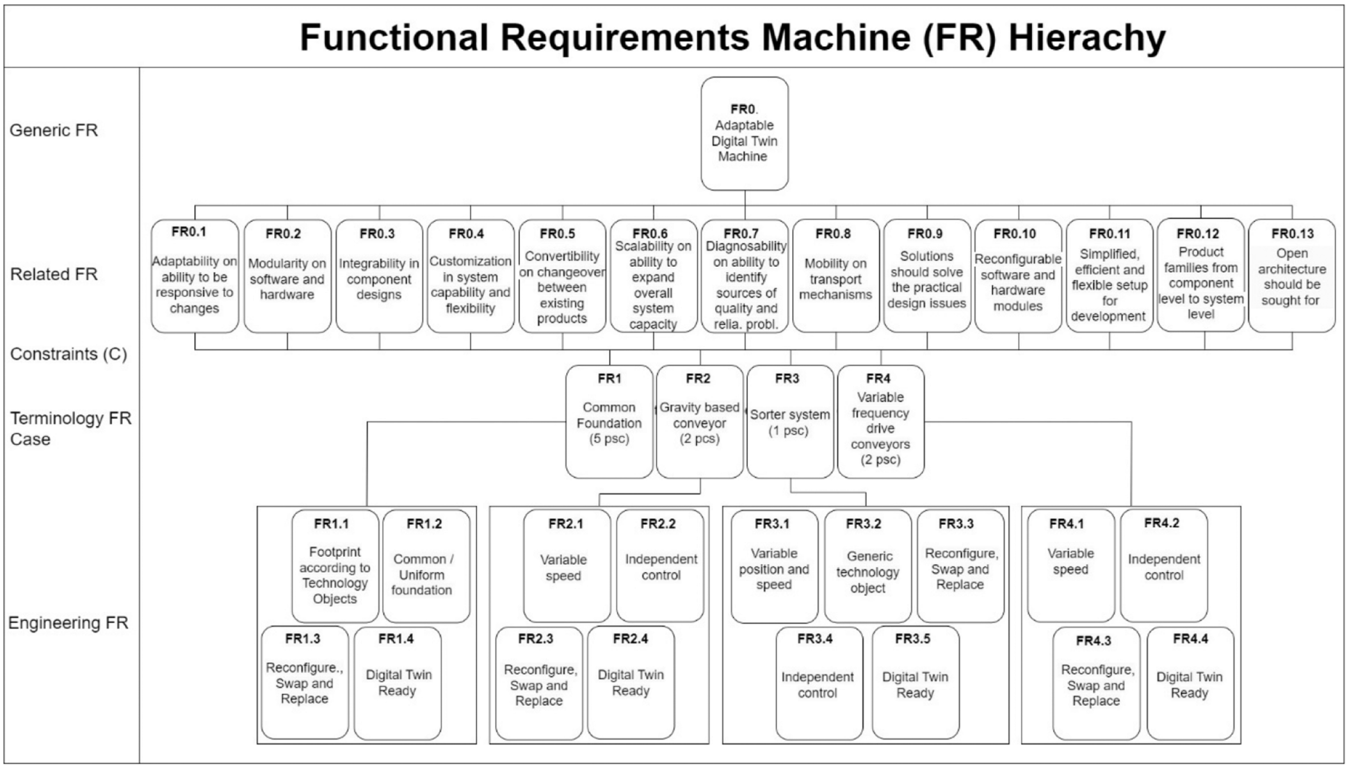

Fig. 4. Functional requirement hierarchy for adaptable machine development.

Siemens VE platform. Therefore, a lot of emphasis was on keeping the modules as independent entities while ensuring design parameters were replicated to maximize the flexibility between the modules.

For convenience and ease of understanding, Fig. 6 has been highlighted regarding reconfigurability to show how the FRs affect the DPs and the specific DMs.

In Fig. 6 above, many of the same characteristics are repeated in all modules, which means simplifications and re-usage of models can be done, saving a significant amount of time during the development. We focus on developing an adaptable machine setup through modularization with a particular focus on the tools facilitating it.

In the process of developing the DMs, DPs were made as a combination of NX part models (1) and simulations (2), in which preliminary mockups were designed in CAD and then simulated in the same environment (NX MCD) to test their functionality and degrees of freedom regarding collision, position, timing of components and machine parts, as seen in Fig. 7. This step could also have included Finite Element Analysis (FEA) and other verification methods, but this was not considered necessary in this case. Instead, the combination of the physics-based multibody simulation NX Mechatronic Concept Designer (NX MCD) and a physical Bosch Rexroth aluminum profile mockups were built to quickly visualize the module's actual sizes and their robustness and weaknesses, as seen in Figs. 5 and 7.

Once the DPs had been created, the highest-rated DPs were selected and used to create the DMs, as seen in Figs. 6, 7, 8, and 9, where three types of platform-specific virtual tools were used to develop and test them. Although these tools were used at different stages of the development and test of the mechatronic machine, we found that by having a pre-modularized setup, reconfigurations of the mechatronic machine could be quickly tested, and different variants could be made based on the original design to test new what-if scenarios, without having to redesign the entire machine.

All aspects of the modularization were supported for the mechanical elements, which were done within Siemens NX and NX MCD, VE environment. Going from CAD-based modeling to multibody dynamic (MBD) simulation and further on to the emulation and VC models as seen in Figs. 3 and 7. The same numerical structure was used on the NX MCD model in Fig. 7 below, as in Fig. 1 and Fig. 3. Starting with the 3D CAD models and continuing to the extended MBD simulation modules, emulation, and VC-ready modules shown individually and combined. These numbers are depicted on the left side of Figs. 7, 8, and 9, corresponding to the VE models' connections with the framework in Figs. 1 and 3.

Fig. 7 should be read from the top left corner to the bottom right corner as indicated by the structures A, B, C, D, E, and F. Showing the complete digital twin machine on the lower right-hand side. DM1 is part of all the modules, while three types of technology objects are used.

For the automation tools, which were Siemens Total Integrated Automation (TIA) and PLCSIM Advanced, the usage of S7 Open User Communication (OUC) protocol made it possible to modularize and contain the control towards the individual modules as seen in (de de de Oliveira Hansen et al., 2023) and Figs. 3 and 8. As previously highlighted in (De Oliveira Hansen et al., 2021; Hansen et al., 2022), the primary behavior logic from the MBD simulation could thus have been transferred directly toward the automation tools, which would optimize the development further. In Fig. 8 below, the OUC for each module has been shown where send, receive, and status blocks have been made, relating to each of the different VE development phases. The individual module logic code is here downloaded and tested at each design module. It, therefore, can operate as separate units and, through the OUC protocol, can operate as a complete machine, as the communication between the modules has been standardized. This is done through a master and slave configuration, in which the modules operate as slaves while another PLC operates as master, as seen in Fig. 3. The PLC master, hence, has two functions: to control the slave's interaction and to communicate with the virtual machine.

As the complete machine was developed with three types of technology objects, the remaining modules mirrored their behavior logic.

In the electrical control where Siemens Simit was used, significant overlaps were found between the chosen control components in TIA and

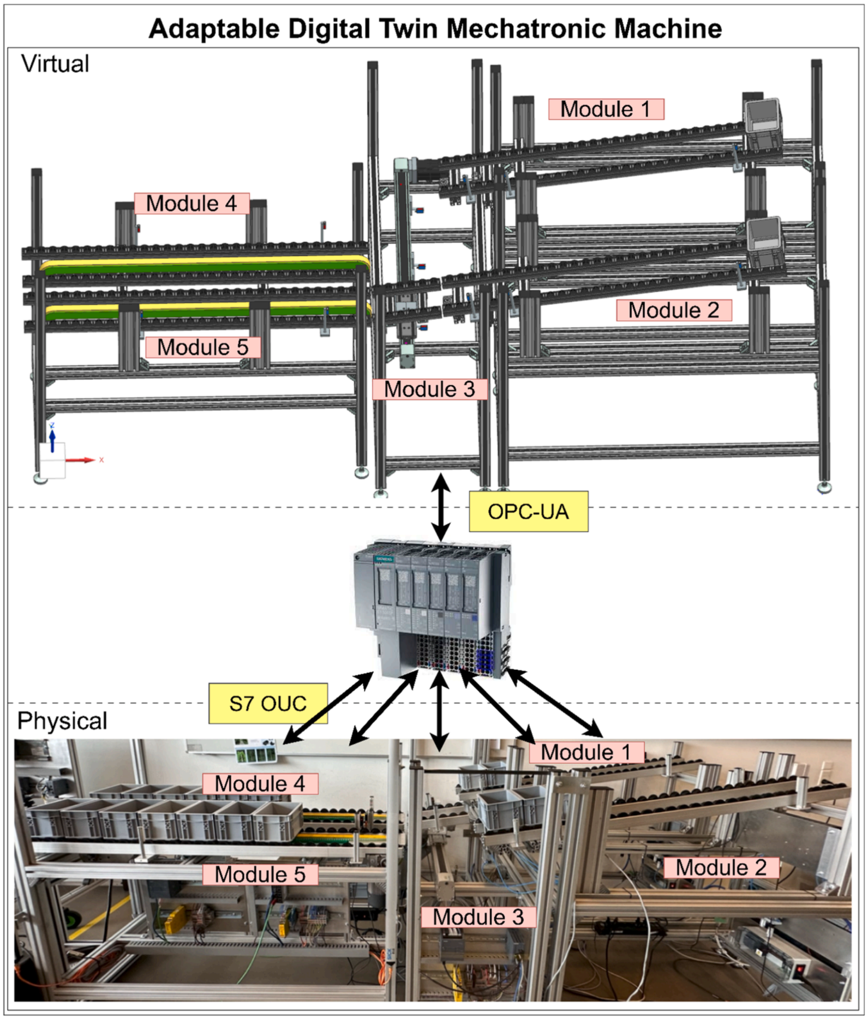

Fig. 5. Modular Machine Family (MMF) for adaptable DT at the University of Southern Denmark.

SIMIT. Here, the reusage of control and information element was implemented through the import/export function between the software tools. Modularization within SIMIT were therefore possible, as seen in Fig. 9, as the IO structure could be easily used in other combination, while the drive modules were already standardized drag-and-drop elements.

The VE SIMIT Fig. 9 above should be read as three modules, each displaying different technology objects. The DM2 relates to the gravity modules regarding input and outputs. DM3 to the sorting module where a stepper motor is used and DM4 is related to the conveyors driven by a regular AC motor through variable frequency drive. For more details on the technical procedures for modeling, simulation, emulation, and VC for the specific tools, see (de Oliveira Hansen et al., 2021). As a rule of thumb, the accuracy of the VE models is lower during simulation and increases towards emulation and VC until the real machine is developed. The accuracy of a given VE model will, however, depend on the detail level and speed of execution. However, it is safe to assume that the VE models' accuracy is high, as prior research has found that quality increases by up to 47% and error handling time by more than 75% (Reinhart and Wünsch, 2007). These findings are sustained in more recent research, which reports a 53% error reduction (Wang et al., 2023).

An OPC-UA connection was established for the digital twin coupling between the virtual and the physical machine, as seen in Fig. 3. Here, a physical Simit dongle could have replaced the need for OPC-UA, creating a faster and more consistent link (Barnowski et al., 2022); however, for this setup, it was not an option. For the digital twin connection, box count and speed information were selected to indicate bottlenecks and other indicators that could visualize the need for reconfigurability within the machine. New situations could then be tested and verified in advance, while changes related to flexibility on the current setup could be made in real-time.

5. Discussion

The finding of this study clearly shows that it is possible to design and develop adaptable digital twins with different types of technology objects and on several abstraction levels. One explanation for this is likely associated with the vendor-specific tools dedicated to machine development. Having a vendor-specific design and development platform means the tool developers/owners are inclined to continuously optimize their tools and performance. Therefore, the Siemens tools related to machine development had been optimized towards re-using standard components and code through associated software libraries, which were incorporated into each VE tool but not specifically towards modules. It was, hence, easy to develop the VE modules, as the tools software structure already facilitated the reuse of components.

It was witnessed that by having the same foundation on mechanical structures, automation logic, and electrical control, variations could quickly be applied and implemented without redesigning everything. This could also be explained through the clear boundary conditions between the modules which make up the machine. Each module

Generic level (FR)	Terminology level (FR) and Constraints (C)	Engineering level (FR)	FR clustering commonalities	Selected Design Parameters (DP) based on Module Driver (MD) scoring.	Design Modules (DM)	
(Gauss et al., 2019; Jiao & Tseng, 1999; Suh, 1998)	(Gauss et al., 2019; Jiao & Tseng, 1999; Suh, 1998)	(Gauss et al., 2019; Jiao & Tseng, 1999; Suh, 1998)	(Gauss et al., 2019)	(Brunoe et al., 2021; Erixon, 1998; Gauss et al., 2019; Jiao & Tseng, 1999; Suh, 1998)	(Gauss et al., 2019; Jiao & Tseng, 1999; Pahl, G. and Beitz, W. and Feldhusen, J. and Grote, 2007; Suh, 1998; Tsukune et al., 1993)	
Functional Requirements (FR) FR0: 2-1-2 Sorter	FR1: Common Foundation (5psc)	FR1.1: Footprint according to Technology Objects	FR1.1, FR1.2, **FR1.3**, FR1.4	DP1.1: Footprint cf. largest technology object	DM1.1: Foundation 1445x690x1240mm	DM1
		FR1.2: Common/Uniform foundation	FR1.1, FR1.2, **FR1.3**, FR1.4	DP1.2: Technology object determines footprint	DM1.2: Same foundation measurements for everything	
		FR1.3: Reconfigure., Swap and Replace	FR1.1, FR1.2, **FR1.3**, FR1.4, FR2.2	DP1.3: 1 module = foundation + top	DM1.3 Flexible connections through Bosch profile	
		FR1.4: Digital Twin Ready	FR1.1, FR1.2, **FR1.3**, FR1.4	DP1.4: Virtual + Physical development + control	DM1.4: Siemens virtual tools + PLCs	
	FR2: Gravity-based conveyor (2psc)	FR2.1: Variable speed	B, E, G, H, I FR1.2, FR2.1, FR3.1, FR3.2, FR4.1	DP2.1: Adjustable angle top module	DM2.1: Adjustment through Bosch profile	DM2
		FR2.2: Independent control	**FR1.3**, FR2.2	DP2.2: OUC / OPC-UA	DM2.2: Profinet / OPC-UA	
		FR2.3: Reconfigure, Swap and Replace	FR1.1, FR1.2, FR1.3, FR1.4, FR2.2	DP2.3: 1 module = foundation + top	DM2.3 Flexible connections through Bosch profile	
		FR2.4: Digital Twin Ready	FR1.1, FR1.2, FR1.3, FR1.4	DP2.4: Virtual + Physical development + control	DM2.4: Siemens virtual tools + PLCs	
	FR3: Sorter (1psc)	FR3.1: Variable position and speed	FR1.2, FR2.1, FR3.1, FR3.2, FR4.1	DP3.1: Stepper / Servo on Festo sledge	DM3.1: TIA technology object module	DM3
		FR3.2: Generic technology object	FR1.2, FR2.1, FR3.1, FR3.2, FR4.1	DP3.2: Stepper	DM3.2: Stepper technology module development	
		FR3.3: Reconfigure, Swap and Replace	FR1.1, FR1.2, **FR1.3**, FR1.4, FR2.2	DP3.3: 1 module = foundation + top	DM3.3: Flexible connections through Bosch profile	
		FR3.4: Independent control	**FR1.3**, FR2.2	DP3.4: OUC / OPC-UA	DM3.4: Profinet / OPC-UA	
		FR3.5: Digital Twin Ready	FR1.1, FR1.2, **FR1.3**, FR1.4	DP3.5: Virtual + Physical development + control	DM3.5: Siemens virtual tools + PLCs	
	FR4: variable speed conveyor (2psc)	FR4.1: Variable speed	FR1.2, FR2.1, FR3.1, FR3.2, FR4.1	DP4.1: AC motor with VFD	DM4.1: TIA technology object development	DM4
		FR4.2: Independent control	**FR1.3**, FR2.2	DP4.2: OUC / OPC-UA	DM4.2: Profinet / OPC-UA	
		FR4.3: Reconfigure, Swap and Replace	FR1.1, FR1.2, **FR1.3**, FR1.4, FR2.2	DP4.3: 1 module = foundation + top	DM4.3: Flexible connections through Bosch profile	
		FR4.4: Digital Twin Ready	FR1.1, FR1.2, **FR1.3**, FR1.4	DP4.4: Virtual + Physical development	DM4.4: Siemens virtual tools + PLCs	

Fig. 6. Exemplified simple table for how FRs lead to DPs and DMs.

working as individual units on the same level. As they are not entwined, errors and mistakes in one unit do not affect the overall system; rather, the machine adapts to the new condition. Likewise, when adding additional modules, the machine adjusts towards the new state as long as the module has the same foundation and boundary conditions, making a structured design approach even more important.

The many types of tools needed to develop the adaptable digital twin could also be seen as a serious hindrance towards adopting this

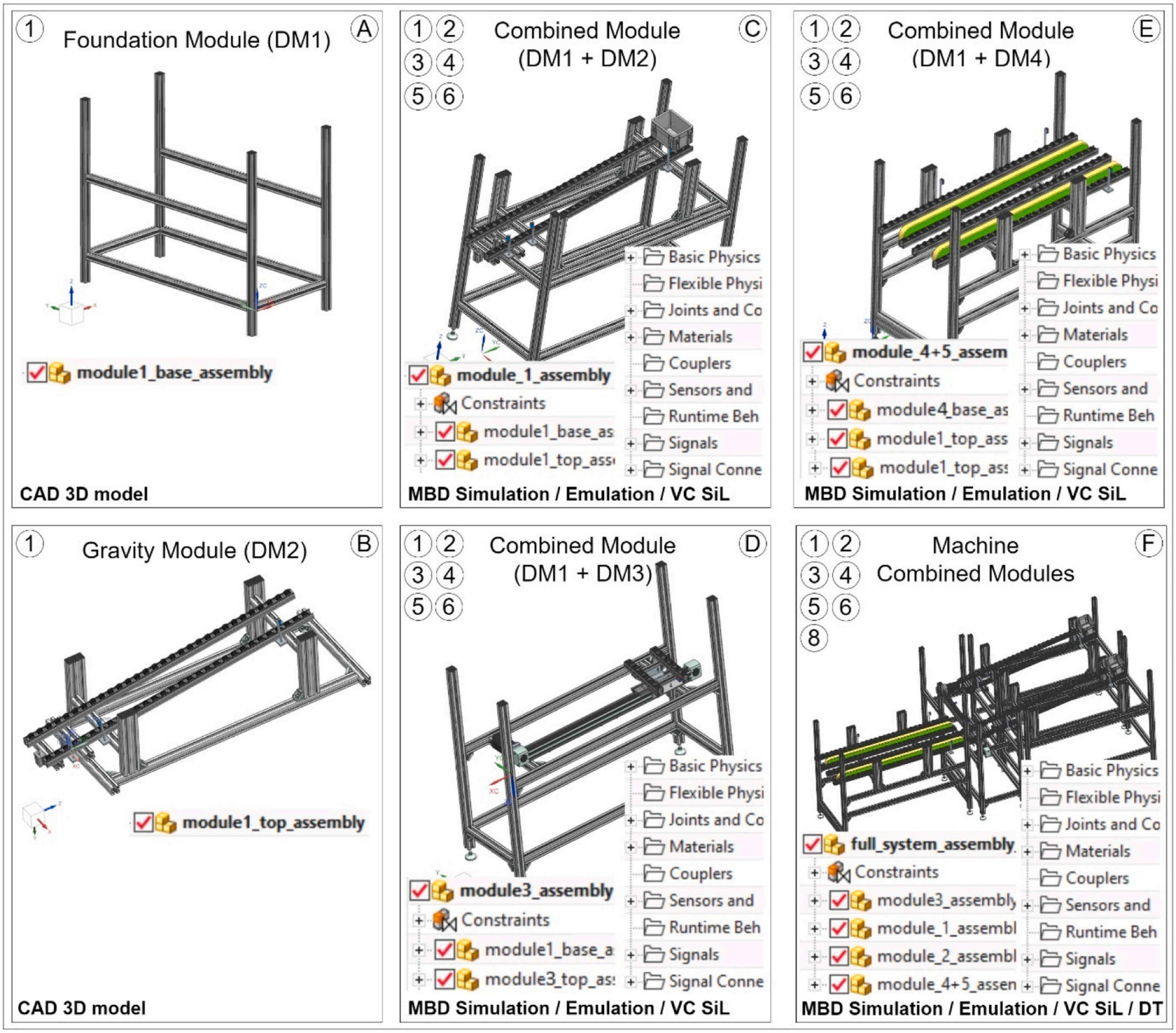

Fig. 7. Modular Machine Family (MMF) on VE Mechanical Design Modules.

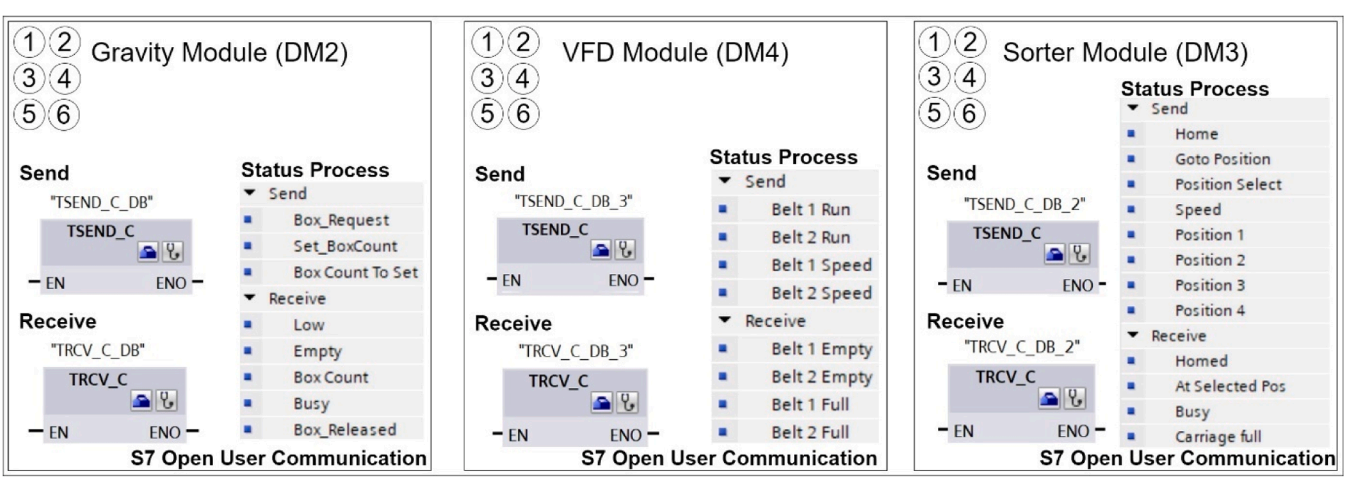

Fig. 8. Modular Machine Family (MMF) for VE Automation Control System Design Modules for S7 OUC Protocol.

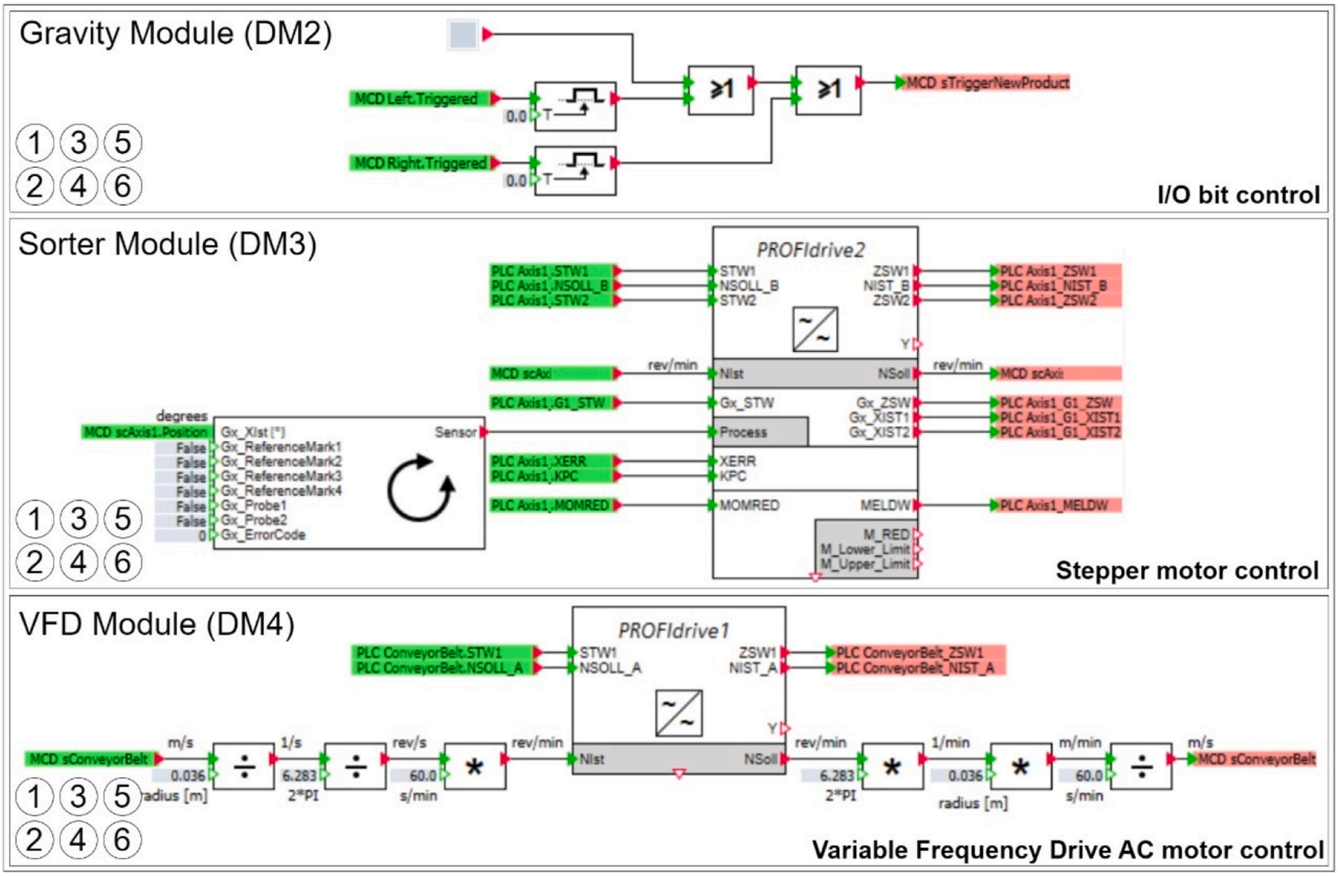

Fig. 9. Modular Machine Family (MMF) for VE Electrical Control Systems Design Modules.

approach, as both license cost and the learning curve increase upfront, although reduced in the long run. Thus, we claim that tool license fees should be differentiated according to the product or machine to be developed instead of a fixed cost per tool. Moreover, to reduce the learning curve associated with VE tools, the knowledge and information shared between the tools could be increased to avoid reoccurring development processes, or alternatively, modularization of different VE behavior models could be made. Helping machine builders overcome these obstacles might provide an excellent opportunity for VE tool developers and companies to facilitate the process.

In this research, most of the literature used is based on journal papers within the field, underlining the validity and importance of the research. All aspects of the digital twin development have been covered, as well as modularization, which included both novel and older established research within the field as seen by, e.g., (Panarotto et al., 2023), (Suh, 1998) and (Gauss et al., 2019) and (Erixon, 1998). Although we were inspired and motivated by many authors and industry, none of these considered a framework for adaptable digital twin discrete mechatronic manufacturing machines and even less regarding material handling. We therefore consider this research a novel game-changer for the discrete industry.

6. Conclusions

In this research, we investigated how to develop adaptable digital twin mechatronic machines through modularization and RMS principles through the Siemens VE tools package aimed towards developing mechatronic machines. These tools were used to design modules on model, simulation, emulation, and VC level, a requirement for creating an adaptable digital twin machine. Having these modules on several VE levels meant efficient development could be made, and new test scenarios could quickly be investigated and tested without starting from scratch. Changes, modifications, and reconfigurations could be done without reengineering the systems due to the clear boundary conditions related to each module on both hardware and software level, increasing their overall adaptability.

The consistent overlaps between the tools meant going from model to simulation, onto emulation, and VC could happen inside the same program tools. Conversions were, thus, unnecessary, and corrections and variations could be made to the modules without making everything anew. However, the reuse of information between the program tools could have been further utilized. The criteria for the DT mechatronic machine were investigated, and as witnessed, many researchers emphasized the need for realism in the design, development, and testing of these machines. The importance of going through each of the individual phases should hence not be skipped, although the detail level can be discussed depending on the type of machine.

Modularized machines are already being developed, as seen at, e.g., VELUX in Denmark; however, to fully utilize the advantages of adaptable DT machine design and development, a continuous and standardized approach must be developed, as demonstrated in the paper. The implications of this paper address machine builders and particularly SMEs. Although the initial resources related to the development of the modules are high, they are reduced over time, from where more rapid changes and developments can be made. The systematic and structured use of VE tools and design will make it easier for machine builders to develop adaptable digital twin machines while reducing the time and resources needed.

During the concluding interview with the Automation Programming Engineer at the Technology Centre at VELUX, three significant aspects were highlighted.

First, the organization set a goal of decreasing the duration required for machine development in retrofit cases by 20% using Virtual Engineering (VE) techniques. However, by employing Virtual Commissioning (VC) Software-in-the-Loop (SiL) methodologies, they were able to surpass their target and achieve a remarkable reduction of 66%.

Second, it is worth noting that over 80% of the errors were identified using VC SiL, thereby leading to a substantial enhancement in the machine's quality. This improvement is attributed to the reduced occurrence of errors during both the commissioning phase and the production process.

Third, the VE modularization framework represents a highly effective approach that has already proven advantageous for VELUX. This is evidenced by the successful integration of modules sourced from various vendors. One potential advantage would arise if the manufacturers of the machines were to include the VE modules in addition to the physical modules. Approximately 50% of the VE machine development at VELUX involves the utilization of pre-existing machine code, mechanical and electrical components, as well as modules. A standardized approach to the reusage of VE machine modules would, therefore, further reduce the development time.

During this investigation, a vendor-specific tool path was chosen to fully understand the opportunities of such a development and avoid being trapped between tool inconsistencies. Therefore, a clear limitation of the research is exploring other types of adaptable digital twin tool combinations to find the perfect mix using the same procedure indicated in this research. Although different types of machines might not need the same detail level used in this investigation, e.g., VC could be done only on the basic level in some situations. Another opportunity could be to investigate open and vendor-independent tools, which would significantly lower the associated costs and thereby proposedly increase the willingness to use time on adopting them. Moreover, although OPC-UA was used for connecting the physical and virtual machine, it would have been beneficial to have used the Siemens Simit hardware device to optimize the vendor-specific setup fully. Finally, this investigation did not explore the effects of updates on the specific setup. This field could hence be further investigated, including merging tools, harmonizing work patterns, and reusing information between tools, all contributing towards a larger adoption and usage of the tools.

CRediT authorship contribution statement

Jesper Puggaard de Oliveira Hansen: Conceptualization, Methodology, Data curation, Validation, Formal analysis, Investigation, Funding acquisition, Writing – original draft, Writing – review & editing. **Elias Ribeiro da Silva**: Conceptualisation, Methodology, Writing – review & editing. **Arne Bilberg**: Conceptualisation, Methodology, Writing – review & editing, Funding acquisition.

Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Data Availability

Data will be made available on request.

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Author Agreement Statement

We declare that this manuscript is original, has not been published before and is not currently being considered for publication elsewhere.

We confirm that the manuscript has been read and approved by all named authors and that there are no other persons who satisfied the criteria for authorship but are not listed. We further confirm that the order of authors listed in the manuscript has been approved by all of us.

We understand that the Corresponding Author is the sole contact for the Editorial process. He is responsible for communicating with the other authors about progress, submissions of revisions, and final approval of proofs.

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