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Cost-efficient digital twins for design space exploration: A modular platform approach

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A R T I C L E I N F O

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A B S T R A C T

The industrial need to predict the behaviour of radically new products brings renewed interest in how to set up and make use of physical prototypes and testing. However, conducting physical testing of a large number of radical concepts is still a costly approach.

This paper proposes an approach to actively use digital twins in the early phases where the design can be largely changed. The approach is based on creating a set of digital twin modules that can be reused and recomposed to create digital twin variants. However, this paper considers that developing a digital twin can be very costly. Therefore, the approach focuses on supporting the decisions about the optimal mix of modules, and about whether a new digital twin module should be developed.

The approach is applied to an industrial case derived from the collaboration with two space manufacturers. The results highlight how the design of the modular platform has an impact on the cost of the digital twin, if commonality and reusability aspects are considered. These results point at the cost-efficiency of applying a modular approach to digital twin creation, as a means to reuse the results from physical testing to validate new designs and their ranges of validity

1. Introduction

The ability to measure the status of products and production equipment, combined with the ability to use digital representations of the same physical product or process, have paved the wave of the 'digital twin' development in industry (Grieves, 2014). The benefits of digital twins are apparent. For example, to better control production processes (Semeraro et al., 2021), enable condition-based maintenance (Errandonea et al., 2020), and exploring new use conditions for existing products (Cimino et al., 2019).

In design, however, physical products are by definition not available. Since the digital twin notion is based on the dual co-existence of a physical and digital definition (Tao et al., 2019), digital twins have not been actively considered in the early phases where the design can be largely changed (Jones et al., 2020), especially in the context of advanced systems such as automotive, aerospace and space products (Bachelor et al., 2019; Martinsson et al., 2021). Rather, the focus over the last decades has focused on replacing physical prototypes and tests with digital model-based simulations (Jones et al., 2019) to reduce the cost of physical testing. At the same time, industries broadly invest in radically new technologies (as in the case of electrification and the introduction of autonomous control), and there is little preceding knowledge to rely on when making predictions – at least in comparison to situations where new products are incrementally refined versions of existing ones. The need to predict the behaviour of radically new products brings renewed interest in how to set up and make use of physical prototypes and testing, which again raises the interest for digital twins during the design phases. As an example, there is currently a large debate in the "new space" community (Öhrwall Rönnbäck and Isaksson, 2018) on how to include more physical testing of a large variety of conceptual solutions - allowing these to fail. Despite the benefits of more physical testing in terms of "lessons learned", combining a designerly approach (Cross, 2001), where a large variety of conceptual solutions are investigated through physical testing is still a costly approach. One alternative could be to use surrogate models built from previous products that have been physically tested (Wang, 2014; Martins and Ning, 2021). This means that the design method, or the "curve" used to predict behavior of alternative solutions in a design space, has been validated by correlating the physical instances. While more cost-efficient, this approach leaves the manufacturer with the risk of not

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knowing exactly to what extent to trust and being confident in the predictions made.

1.1. Motivation and research questions

This paper builds on the growing interest on using digital twins to reliably explore large design spaces (e.g., Jones et al., 2020). However, this paper considers that developing digital twins for several unique design concepts can be very costly (West and Blackburn, 2017). Therefore, the benefits of digital twins used for design space exploration need to be traded against their development costs. The research work has then started around this first research question:

RQ1. : How to create digital twins for design space exploration in a cost-efficient manner?

The results from this work led to the idea of separating the product into a set of digital twin modules that can be reused and recomposed to create digital twin variants - building a modular digital twin platform. Most established manufacturers already rely on developing modular platforms that expect to be configured to create variants (Jiao et al., 2007; Otto et al., 2016). This research adapts the product platform concept to digital twins. However, applying a product platform notion requires to resolve the trade-off between reusing existing digital twin modules and developing new digital twin modules (to gain the ability to predict product behavior at higher performances). Therefore, this second research question has been formulated:

RQ2. : How to identify and compare modular digital twin platform alternatives for design space exploration?

To answer these questions, the paper starts by examining the literature on digital-twin based design and modular platform development, to extract the key elements for how to approach the design and creation of a modular digital twin platform. Afterwards, the approach is described and applied on 1) an illustrative example and 2) an industrial case derived from the collaboration with three space manufacturers developing advanced systems for satellite electric propulsion.

2. Background

In this section, an overview of previous research on how to use digital twins for design space exploration is provided. By analysing the benefits and challenges of digital twin-based design, the potential of using a modularization approach can be highlighted.

2.1. Digital-Twin based design: opportunities, challenges, and the potential of modularity for cost-efficient digital twins

Recent research (e.g., Leng et al., 2021) has described the opportunities and challenges of digital-twin based design. For example, the digital twin system directly conducts validation and test that can quickly identify malfunctions and inefficiencies, rule out the design mistakes, and test the practicability of a physical solution when in execution. Also, the digital twins-based design is supposed to enable the validation of system performance in a cost-efficient manner.

At the same time, literature has focused on several challenges when applying a digital twin notion in design (Vogt et al., 2021), especially in the context of disruptive and radical products (Bertoni and Bertoni, 2022) and in product-service systems (Machchhar, et al., 2022). One of the main concerns is design reconfigurability to rapidly modify and explore the design space. These reconfigurability aspects challenge the "twinning" capabilities between the physical and digital definition of a design variant, i.e., its physical-to- virtual (P2V) connection. In situations in which the P2V cannot be automatic and high-fidelity, literature has introduced new definitions, such as "digital shadows" (Kritzinger et al., 2018) characterized by an automated one-way data flow between the state of an existing physical and digital object, but not vice versa. Also, the notion of 'digital model' as been emphasized in design related literature. Literature in field of Cyber-Physical Systems (CPS) describes those models that purely exists and are merely meaningful within the cyber space as Cyber Twins (Tao et al., 2019). By inter- connecting multiple Cyber Twins is then possible to represent CPS with precision. Yet, these twins do not feature those interactions, communication, and collaboration capabilities between physical and cyber space that are proper of the DT.

Independently on the type of physical-virtual connection that is established, there seem to be an agreement that physical-digital reconfigurability is the prerequisite of variant design (e.g., Jones et al., 2020). In this context, the notion of modularity is emphasized, either explicitly or implicitly. For instance, Leng et al. (2021) apply the notion of 'open architecture' to digital twin-driven rapid reconfiguration of the automated manufacturing system. Liu et al. (2021) model the physical system in terms of Function, Structure, Behavior, Control, Intelligence, Performance to perform a digital twin-based design of the configuration, motion, control, and optimization of a flow-type smart manufacturing system. Therefore, it is interesting to review how modularity has been systematically applied in the context of product platforms, to understand how the notion of a product platform can be used to design cost-efficient digital twins for design space exploration.

2.2. Modularization of product platforms: key strategies

Several modularization strategies have been defined to aid the design of a modular product platform (Bonev et al., 2015). In these strategies there are two important aspects: 1) product decomposition and 2) "modularity rules" to decide upon good candidates for modules.

The most common way of decomposing a product into modules is through a function-based separation (e.g., Ulrich, 1995; Erixon, 1998; Hölttä-Otto et al., 2008), starting from the principle that product modules are function-carrying units (Bergsjö et al., 2015). Using a function-based separation of the product, modules can be clustered based on the functions that they share among each other. This enables a cost-efficient way of identifying modules that can be pre-produced and later combined, depending on the level of functionality that is offered to the different customer segments. However, how to functionally decompose a product into modules is not straightforward (Otto et al., 2016), especially in the case of integral products, where a single monolithic component fulfills many functions (Raja et al., 2018). The same difficulties apply for multi-functional integrated product such as mechatronic systems. These products often present a comparable presence of mechanical elements mixed with electronics and software (Heimicke et al., 2019). Since software and electronic elements are more difficult to be separated into physical components (compared to mechanical elements), a physical-based decomposition of modules is not straightforward.

Another stream of research has focused on the trade-offs involved in adopting a modular platform thinking in manufacturing (e.g., Jiao et al., 2007, Thomas et al., 2014). While a modular platform has the ability to offer variety to customers in a cost-efficient manner, something must be traded off to obtain those advantages. This is often the performance of each individual variant (Kamrad et al., 2013), because performances are compromised by reusing components from other products leading to sub-optimization. On the other hand, the advantages for manufacturing of platform approaches are up to 30–50 % of the development and production costs (Bremmer, 1999). Therefore, literature has focused on how to support the decisions about different methods have focused on applying a set of modularity rules whether the advantages of reusing a module over the product family overcomes the advantages gained in optimizing the performances of the individually design products (Otto et al., 2016). Erixon (1998), for example, applied functional decomposition to identify product functions, and mapped the functions against "modularity drivers" (e.g., carry over, upgrading, recycling), in an approach similar to QFD. In this method, called Modular Function

Deployment (MFD), the most important functions dominated by the same modularity drivers are good candidates for a module. Gonzalez-Zugasti and Otto (2000) apply product platform constraints (family, sharing, and compatibility constraints) as decision criteria in a genetic algorithm to tradeoff with the attributes of the individual products (functional performances and unit costs). The approach allows to select the right combination of common and unique modules for each desired product, as well as to choose the design targets for each of those modules. Suh et al. (2007) developed an approach in which the platform constraints are not pre-assigned but emerge instead after solving the optimization problem in which the market shares for the different variants are calculated to optimize a financial metric, Net Present Value (NPV).

In general, these quantitative approaches aim at optimizing the *bandwidth* of the platform (Levandowski et al., 2014). Since the platform is designed to meet a range of customer requirements (Martin and Ishii, 2002), the bandwidth considers both the physical and functional properties of a product (such as the ranges of engines that a car can have), which are connected to the customer requirements. Therefore, there is a bandwidth both on the requirements and well on the design solutions that fulfil such requirements (Levandowski et al., 2014).

3. A modular platform approach to cost-efficient digital twins for design space exploration

As the literature review suggests, product decomposition and modularity rules represent hey elements that are leveraged to create cost-efficient product platforms able to generate large product variants. Following the same reasoning, this paper looks into how to apply modularity to develop cost-efficient digital-twin variants to be used for design space exploration.

3.1. Research methodology

The approach and its impact on cost-efficiency in the early design stages is demonstrated using 1) an illustrative example and 2) an industrial case study:

1. The illustrative example considers a case in which a manufacturer wants to find a solution to sustain a certain Force (F) requested by customers. One possible solution to this design problem is a cantilever beam rigidly fixed, defined by critical design parameters (for example, the module of elasticity E). The purpose of this simple example is to highlight how the choice of the digital twin platform (composed by its physical and digital definition) has a profound impact on the cost and the ability to explore the design space for a large range of customer requirements (in this case, the Force F to be sustained).
2. The industrial case study is derived from an undergoing EU-funded space development project, where three manufacturers are involved in the development of an electric propulsion systems (EPSs) based on a Hall Effect Thruster (HET) technology (Goebel and Katz, 2008). An HET EPS is composed of three main parts (Fig. 1): 1) the thruster unit (TU), which transforms electric energy and propellant into T; 2) The power processing unit (PPU), which supplies the thruster with electric power from the satellite bus and manages it; 3) the flow management system (FMS), which ensures the regulation of propellant to the TU from a propellant tank and manages it.

Fig. 1 displays the main parts of an EPS in a simplified schematic. The figure also highlights the main interactions and interfaces: mechanical (red), electrical (green), software (grey) and fluidic (blue). The figure highlights that an EPS is a multi-technological system, presenting a mix of mechanical, electronic, fluidic and software elements.

Fig. 1 illustrates how the industrial case study has been used to extend the approach to more complex functions, which can be provided by mechanical parts, electrical elements or software code. This case study is presented using a series of products that are of a smaller size than the ones concerned in the current project. This is to protect company-sensitive information, while at the same time to be able to show a data-driven design problem with data extrapolated from literature (e.g., Diome at al, 2017) and publicly available material (Ducci et al., 2013). However, the design problem described below is closely related to the business concerns of the manufacturers involved in the industrial project. The authors believe that the lack of disclosure of real data (while undermining the complete transparency of the results) is still relevant to fulfill the purpose of the case study, which is to demonstrate the methodology in an industrially relevant set-up.

3.2. Functions of a digital twin and predictive capabilities for design space exploration

The industrial case study highlighted that to be used for design space exploration, the digital twin needs to support the decisions about whether the new design meets or exceeds the requirements given by the customers (*Req*). This assessment should both consider present of future requirements. These requirements derived from the functions that the product should fulfill. By applying a functional decomposition, regions

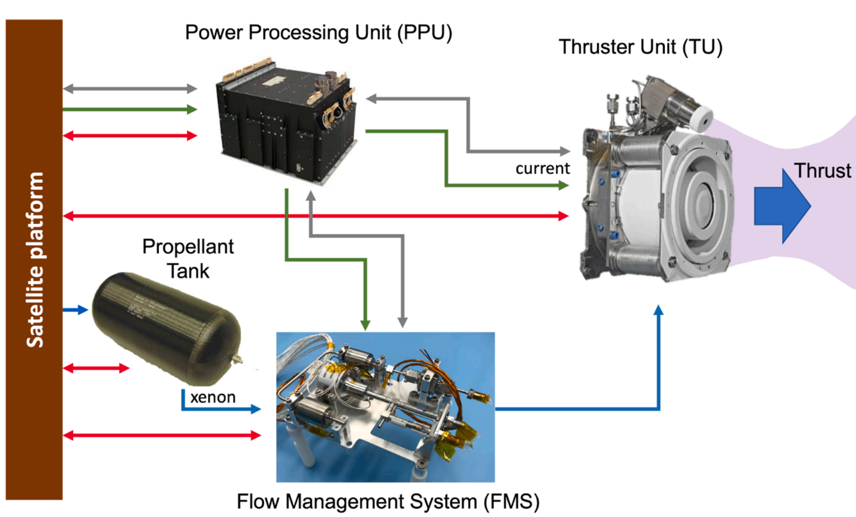

Fig. 1. Simplified schematic of a typical electric propulsion system (EPS) configuration. (adapted from Lorand et al., 2011).

of the design that fulfil one function can be identified as modules, as described in modularization literature (Ulrich, 1995; Erixon, 1998; Hölttä-Otto et al., 2008). Fig. 2 highlights how the digital definition fulfills the same function as the physical one in the cantilever beam example (Sustain Force).

The figure also highlights two different "attributes", or capabilities, of a digital twin for design space exploration:

- the bandwidth of capability prediction, denoting the bandwidth of design capabilities that can be predicted. In Fig. 2, this is denoted as a vector of forces that can be predicted [F_{min}, F_{max}].
- the prediction accuracy of the digital definition (*AccuracyDT*), denoting the accuracy of prediction made. In Fig. 2, a simple multiple linear regression model is used, and a classic coefficient of determination (R^2) is taken as a metric for accuracy ($R^2 = 0.72$). In real examples however, the capability to be predicted may not be numerical, and may not be continuous.

The values for the bandwidth and the accuracy come from previous variants of the cantilever beam that have been manufactured, tested and validated (85 instances in this simple example). The data coming from these testing activities are connected to the module as shown on the right of Fig. 2.

It must be noted that the connection between the data and the module shown in Fig. 2 do not feature those interactions, communication, and collaboration capabilities that are proper of the Digital Twin. This is because this paper focuses on the ways a modular digital twin platform can be designed and compared, rather than making a clear-cutting distinction between the 'twinning' capabilities than can be enabled by the platform. In this paper, the twinning capabilities embedded in each module can take any form, from a digital twin to an analytical model or a 'digital model' (Kritzinger et al., 2018) made from Cyber Twins (Tao et al., 2019) that have been inter-connected to describe a Cyber-Physical System (CPS). However, how the approach differs among a virtual model, a cyber twin, a digital shadow or a "whole" digital twin (with automatic data transferring between the physical and the digital definition) is necessary and left for future work.

3.3. Creating modular digital twin platform alternatives: cantilever beam example

By decomposing the digital twin according to the function, a set of independent modules can be identified, creating a modular digital twin platform. At the same time, alternative modules to fulfil the same function can be identified, creating alternative modular platforms. There are many methods to perform this decomposition and module identification. In this paper, the Enhanced Function-Means tree (EF-M) model is used (Johannesson and Claesson, 2005; Müller et al., 2019). In EF-M, the Functional Requirements (FRs) of a system are connected to their Design Solutions (DSs) following the 1:1 principle of axiomatic design (Suh, 1990). Also, EF-M allows to model the interactions, dependencies, and interfaces between DSs (through 'interacts_with' objects, iw). It has to be noted that the choice of EF-M is mainly opportunistic in this paper, and the question about the most appropriate methods to design a modular platform are left for future work.

In the example of the cantilever beam, the manufacturer possesses two modular platform alternatives. The first modular platform (modular platform A) consists of the same single 'cantilever beam' shown in Fig. 2. The second modular platform (modular Platform B, Fig. 3) contains the same cantilever beam module to fulfil the function of "sustain force", but in addition another module is used in combination (a bracket which fulfils the function "support beam", providing a reaction on the beam).

This example considers two requirements: the Force (*F*) requested by customers. and the deflection (δ) at the end of the beam. To make the example more interesting, the digital twin of modular platform A has a higher digital twin accuracy ($R^2 = 0.72$) that the modules of platform B (R^2 =0.61 for the beam and $R^2 = 0.64$ for the bracket).

The reason for these different values of R^2 is because the digital twin of modular platform B relies on fewer module variants (85 for modular platform A and 30 for modular platform B). Also, modular platform A possesses a higher bandwidth of capability prediction, compared to modular platform B (Table 1).

Table 1 does not show all the variants considered but shows instead the upper and lower bounds of the prediction bandwidth capability. This means that for higher forces outside the prediction bandwidth, the manufacturer can rely only on the predictions made by the digital twin, and its associated prediction accuracy. In fact, for a uniform cross section beam under elastic deformation, there is already a (classic) numerical model. Even if the beam has a non-uniform cross section, there are ways to relatively accurate predict forces and deflections numerically. However, these numerical or mechanics-based approaches to predicting deflection, do not include the existence of some variation that is not easily controlled (e.g., non-nominal shapes and loads), or potentially a non-homogenous material with a relatively large spread (uncertainty) in physical properties (e.g, stiffness).

3.4. Creating modular digital twin platform alternatives: HET case study

The industrial case study has focuses on the Flow Management System (FMS) of the HET, therefore, only alternatives for the digital twin platform of the FMS are displayed. A first solution to satisfy the FMS functions is shown in Fig. 4. This system is shown as a digital twin platform, where the physical (actual system) and the digital definitions for each module are available. Each digital definition (here symbolized

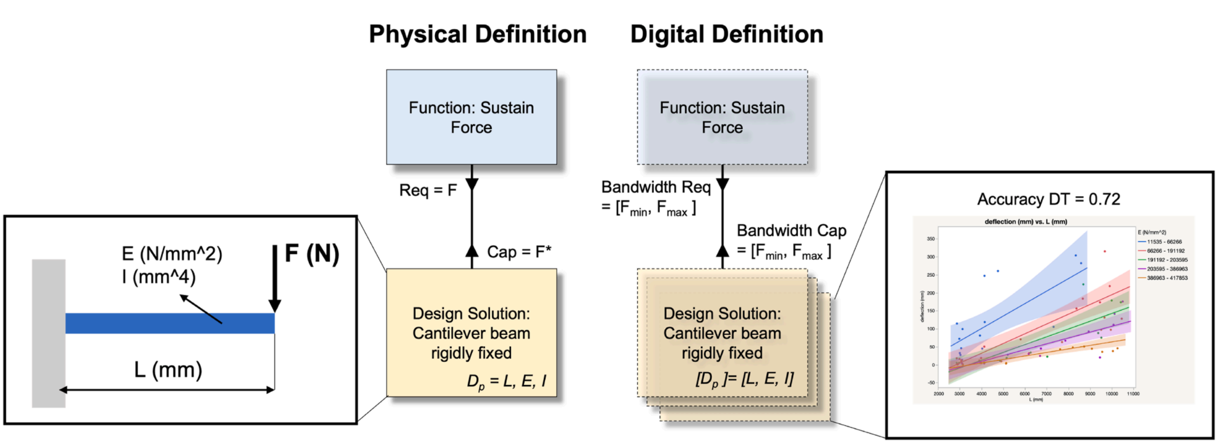

Fig. 2. Elements of a Digital Twin Module in the cantilever beam example.

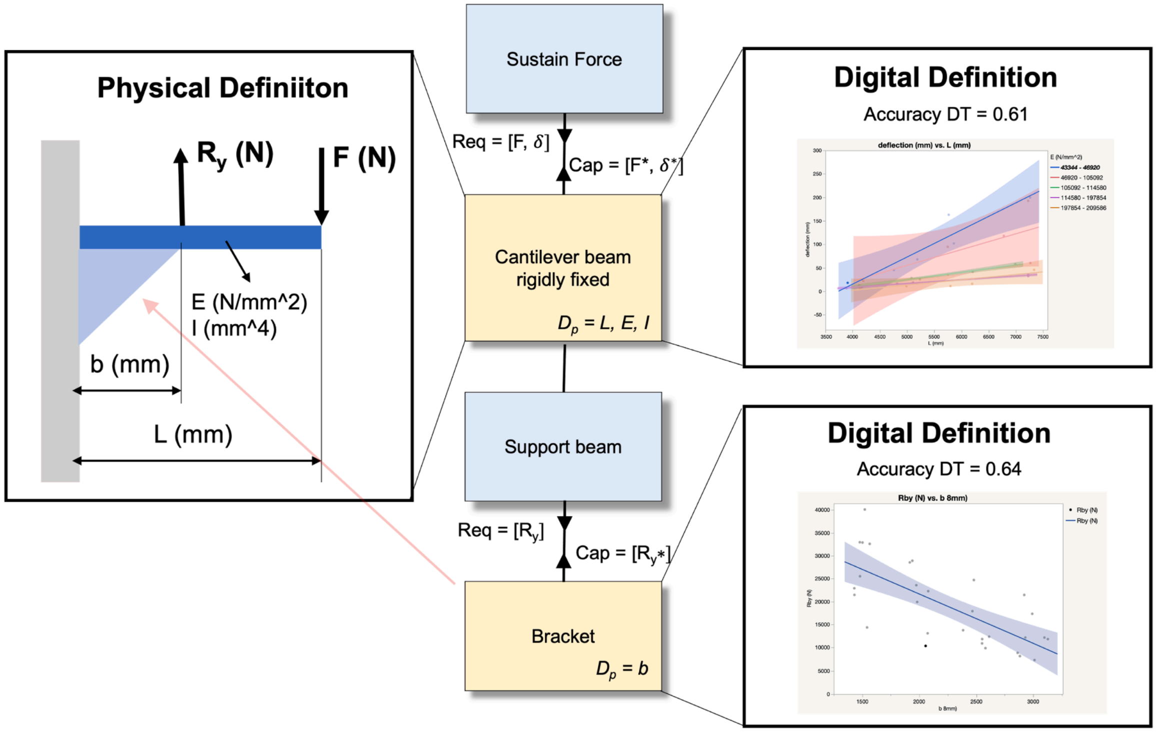

Fig. 3. Modular platform B: cantilever beam with bracket.

Table 1
Available module variants for Modular Platform A and Modular Platform B.

		Modular Platform A Cantilever Beam		Modular Platform B supported Beam	
Number of available variants		85		30	
Prediction Bandwidth Capability	Units	Lower bound	Upper bound	Lower bound	Upper bound
Force (F*)	N	2800	10,500	3800	7200
Deflection (δ *)	mm	49.10	111.07	35.37	84.39

by a CAD model) is connected to a set of real data coming from testing, fitted using prediction models.

An FMS fulfils essentially two main functions. The first function is to reduce the propellant pressure from the tank (e.g., from 180 bars down to 10 bars). One solution to fulfill this function is to use a mechanical valve. As the name suggests, the working principle of a mechanical valve is purely mechanical: the pressures at the inlet and outlet of the valve automatically adjust to match the force of a preloaded spring (O'Sullivan et al., 2006). Therefore, the mechanical valve represents the first module. The requirement for this module is the pressure drop requested by the valve ($\Delta P = P_{in} - P_{out}$), and the digital definition of the mechanical valve needs to analyze whether the provided capability meets this requirement.

The second function for an FMS is to control the propellant mass flow rate. The need for this function is due to two main reasons 1) to be able to operate the thruster in different modes and operations (i.e., flexibility "in orbit") and 2) to compensate for instability of flow at the end of the pressure regulation mechanism (in this case, the mechanical valve). The requirement for the solution to this function is the flow rate variation that can be realized ($\Delta\dot{m}$). One solution (or module) to fulfill this function is to use a "thermothrottle" mechanism (Kinefuchi et al., 2020): the principle is to increase the xenon viscosity by an electrical heating of a flow restrictor, and the flow rate is limited due to the increase in flow friction. Consequently, the thermothrottle uses a heater powered by the PPU which regulates the xenon flow rate. This means that there are electrical and software connections and interfaces to the PPU, and these are visualized by green and gray "iw" connections in the EF-M. Also, a fluid (blue) connection is shown from the tank to the mechanical valve, and from the valve to the thermothrottle. **Error! Reference source not found.** also gives an example for how a digital definition for the thermothrottle module is created, exploiting previous tests. In this case, public data is taken from Diome at al. (2017), and it visualizes the $\Delta\dot{m}$ achieved when varying the heater current.

There are more modules available to fulfill the function "reduce propellant pressure from tank" other than the "mechanical" FMS (Module-01), shown in Fig. 5These module alternatives are visualized in Fig. 5. One way is to use a "bang-bang" pressure regulation system (Koppel and Estublier, 2005; Module-02 in Fig. 5). With this system, a software Control Unit can be programmed is such a way that the timing of the valve openings can be varied so that the pressure drop can be realized.

In a bang-bang pressure regulation system, the function "reduce pressure from tank" is fulfilled as follows:

- If the gas pressure at the outlet is smaller than a pre-set threshold pressure (measured by a Low-Pressure Transducer – LPT), a first solenoid Isolation Valve (IPV1) is opened, and the gas (xenon) flows from a Tank containing xenon in high pressure to an intermediate Plenum Tank. The gas is then stored and expanded in the Plenum Tank. Note that in Fig. 4, the Tank is considered outside the system boundaries, and only the Plenum Tank is visualized.
- After a pre-set time has passed, the IPV1 is closed.
- After another pre-set time has passed, a second solenoid Isolation Valve (IPV2) is opened for a programmed period, and the low-pressure gas flows from the Plenum Tank to the outlet. The LPT then measures and ensures that this pressure is below the pre-set threshold. After the pre-set time has passed, the IPV2 is also closed.

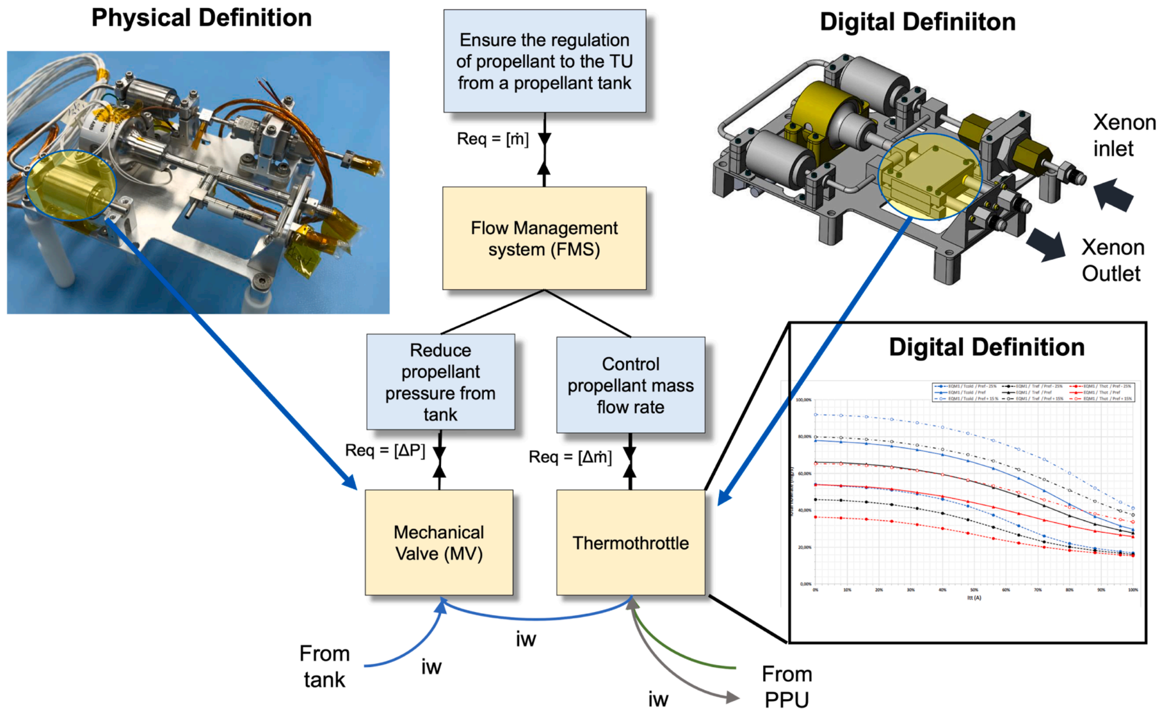

Fig. 4. Modular Platform for the Flow Management System. Photo of the physical product taken with courtesy from van Put & Kuiper (2021).

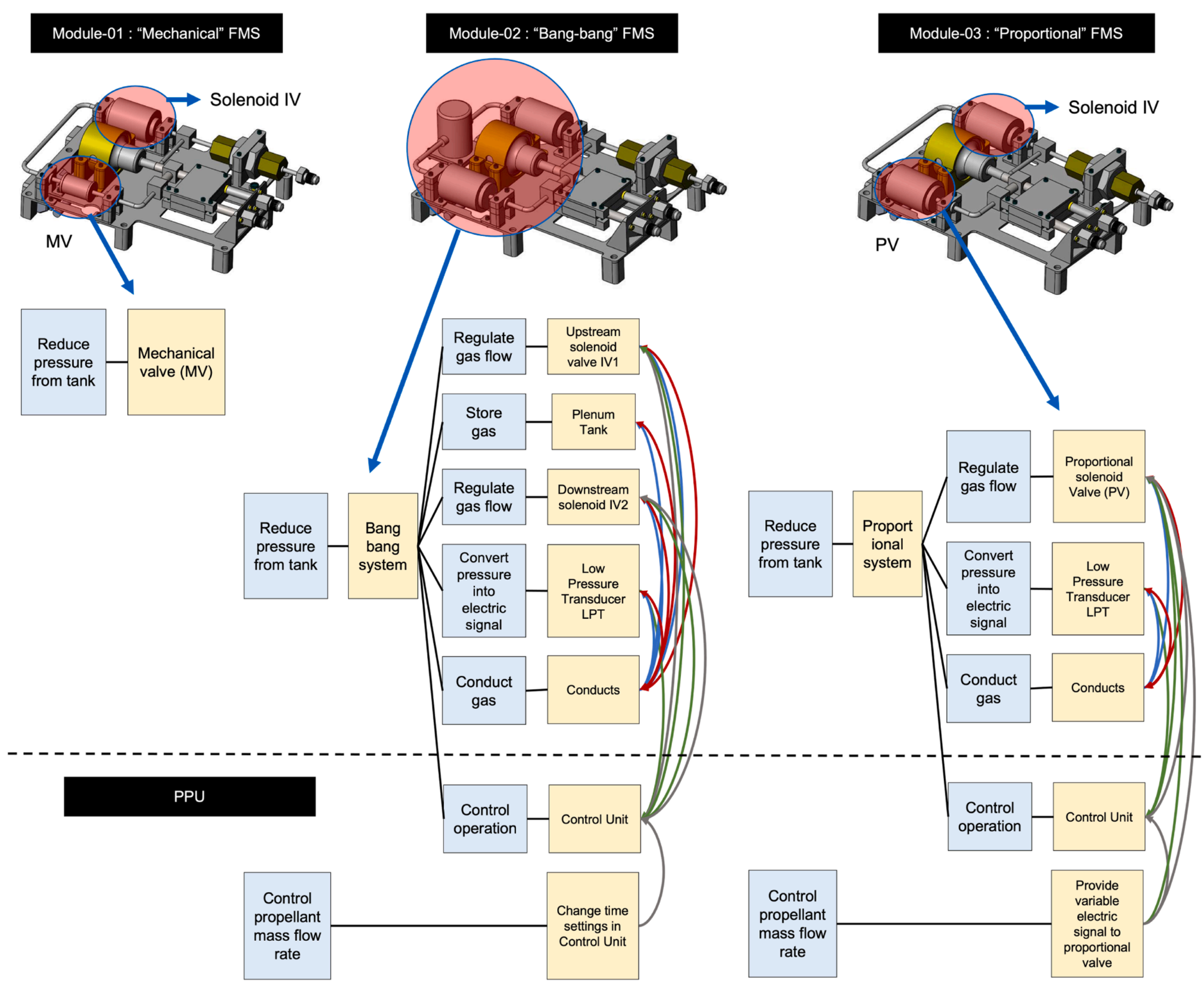

Fig. 5. Alternative Modular Platforms for the Flow Management System.

The two solenoid isolation valves (IPV1 and IPV2) operate in "on/off" mode (Jing et al., 2011), meaning that the valves are either entirely opened or entirely closed. Therefore, the valves themselves do not reduce the pressure drop operated the system. Such reduction is made possible by the timely opening and closing of the valves operated by a Control Unit (CU) that takes as input the signal provided by the LPT.

An interesting aspect of the bang-bang pressure regulation system is that due to the software control, the timing of the valve openings can be varied so that different pressure drops can be realized. What is interesting is that this variation in pressure drops allow to control the propellant mass flow rate. Compared to the system described in Fig. 5, the function "control propellant mass flow rate" is now moved to the PPU instead, so that the thermothrottle module is not needed anymore to realize this function. In the EF-M tree in Fig. 5, this is symbolized by a software connection from the DS "change time settings in control unit" and the DS "control unit" under the PPU.

A third alternative would be to choose a "proportional FMS" (Module-03). This alternative is interesting for the space manufacturer since it takes advantage of new technological advancements in the individual components of an FMS. In this design, a single proportional solenoid valve (Boyle and LaGrotta, 2018) is controlled to fulfil both the function of "pressure reduction" and "control the mass flow rate". In a proportional valve, a variable current is applied to the valve's solenoids. Therefore, proportional valves do not operate in on/off mode (such as in a bang-bang system) but are opened and closed at intermediate steps. The use of a proportional valve allows to remove the upstream "on/off" solenoid valve IV1 and the plenum tank (compared to the bang-bang system), together with their electronics and software controls. The CAD models of Fig. 5 also present an upstream solenoid Isolation Valve (IV) for the mechanical FMS and the proportional FMS. However, this valve does not contribute to fulfil the pressure reduction function. This valve (normally opened) is used to be able to cut off the flow of gas from the tank in case of anomalies (therefore this valve has a reliability-related function). For this reason, this valve is not visualized in the EF-M trees in Fig. 5, because it belongs to another function that the ones considered in this case study.

The crucial part of this step is to identify and visualize the interfaces between the digital twin modules, with the objective of minimizing the possible interactions, and to strive for as much independence as possible between the parts of the system. This is shown in Fig. 6. The figure displays a DSM of the different platform alternatives, transferred from the EF-M representation.

The focal point of the figure is to highlight how the "proportional FMS" is the platform with the least number of interfaces to the PPU and the TU. Only two interfaces (electrical and software) are connected to the PPU, and only one fluidic interaction to the TU. Also, the "bang-bang FMS" presents the least number of interfaces, but it has more interfaces within the module (Fig. 6). The fact that the "proportional FMS" is the platform with the least number of interfaces to the PPU and the TU means that the designer has less interfaces to control and optimize. After the platform alternatives are identified in terms of their modules and interfaces, the available data is connected to the modules, in order to create a modular digital twin platform to exercise to find the alternative that meet the defined requirements at the lowest overall cost. Fig. 7 show examples of the data collected.

For the Thruster Unit, data is adapted from Ducci et al. (2013) and connects test data regarding the thrust at the variation of the mass flow rate ($\dot{m}$) coming from the FMS and the voltage (V) supplied by the PPU. For the mechanical valve, data is derived from (O'Sullivan et al., 2006), and connects the reduction of pressure (ΔP) made by the avilable valve variants tested in the past. For the bang-bang FMS, data is derived from Naclerio et al. (2012) and fort the proportional FMS, data is derived from Fendler et al. (2017) and Lenguito et al. (2019). The thermothrottle module is connected through public data is taken from Diome at al. (2017) and displays the $\Delta\dot{m}$ achieved when varying the heater current.

3.5. Trading off predictive capability and digital twin costs: cantilever beam vs. supported bream

This paper extends the existing modularity strategies by considering the bandwidth of capability prediction and the accuracy as "modularity drivers" (Erixon, 1998) to consider the need to reuse the digital twin module for future designs. The principle is that a good candidate for a digital twin module is the one that enables to predict a large variety of

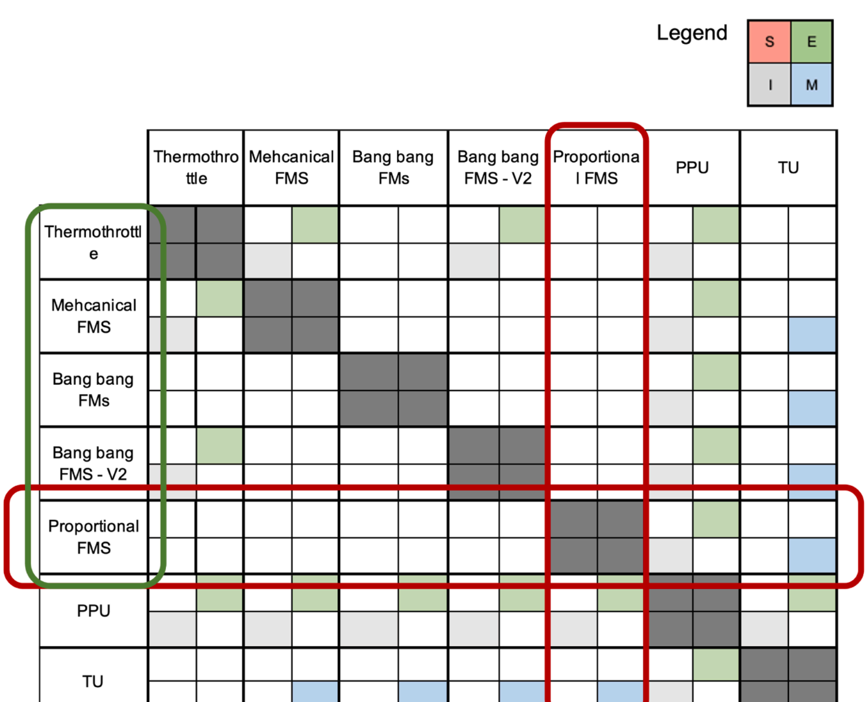

Fig. 6. DSM showing the difference interfaces between digital twin modules.

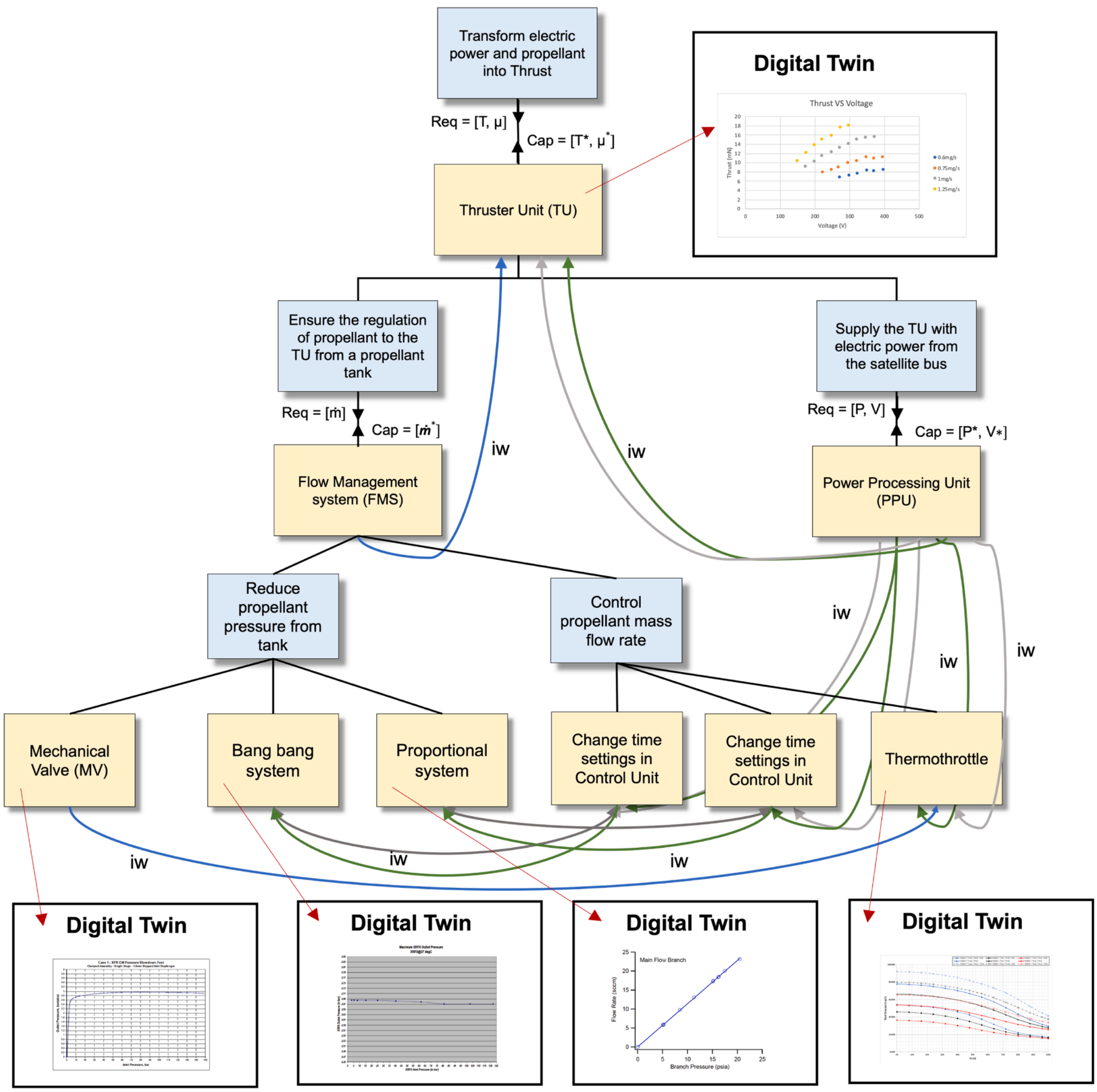

Fig. 7. Available data connected to the modules that compose the Modular Digital Platform Twin.

Table 2
Results for Modular Platform A and Modular Platform B. The bold text means that a new digital twin is created.

		Modular Platform A - cantilever Beam			Mofular Platform B - supported Beam		
Requirements		Cust. 1	Cust. 2	Cust. 3	Cust. 1	Cust. 2	Cust. 3
F (N)		> 24,000	> 26,000	**> 28,000**	> 24,000	**> 26,000**	> 28,000
δ (mm)		< 130	< 70	**< 50**	< 130	**< 70**	< 50
Design Parameters							
Module 1	L (mm)	2800	2800	**2800**	3800	**3800**	3800
	E (N/mm^2)	209,000	400,000	**400,000**	209,000	**209,000**	209,000
	I (mmm^4)	67,000,000	80,600,000	**140,000,000**	67,000,000	**67,000,000**	67,000,000
Module 2	b (mm)	0	0	**0**	1600	**3200**	3200
Capabilities							
F* (N)		24,000	26,000	**28,000**	24,000	**26,000**	28,000
δ * (mm)		120.61	69.19	**48.65**	122.02	**19.07**	47.37
Costs							
Module 1 Physical Definition Cost (k€)		0.37	3.48	**4.60**	0.48	**0.48**	0.48
Module 2 Physical Definition Cost (k€)					0.77	**3.06**	3.06
Module 1 Digital Definition Cost (k€)				**9.20**		**0.95**	
Module 2 Digital Definition Cost (k€)						**6.13**	
Total cost of digital twin (k€)		0.37	3.48	13.8	1.25	10.62	3.54
Total Platform Cost (k€)		**17.7**			**15.4**		

capabilities with high accuracy at the minimal cost for the entire platform. In the best-case scenario, the design solution is a previous variant of the cantilever beam module (tested and verified), and its capability falls into the bandwidth [$F_{min} < F^* < F_{max}$]: if the accuracy of the prediction is deemed as acceptable, the design solution is reused, and only the cost to develop the new physical definition is incurred. If the design solution is not a previous variant and its capability falls outside the predicted bandwidth [$F^* > F_{max}$], the designer can physically develop an individual design of this solution and update its digital definition after physical testing and verification. In this case, the digital twin is updated, and both the costs to develop the new physical and digital definition are incurred. This paper argues that this second strategy may be too short-sided, especially in the case where the physical testing and the subsequent "digitalization" of its results are very costly. In these situations, even more costs may be incurred if higher requirements for this module are requested by the customers (new physical and digital definitions need to be developed). Therefore, there is a need to consider different modular digital twin platform alternatives, and to trade their predictive capabilities against their costs. These results, considering three customer segments, are summarized in Table 2. Customer segment 1 is less demanding, while segment 3 imposes very stringent requirements on both the force and the deflection.

The focal point of Table 2 is to highlight how the design of the modular platform has an impact on the cost of both the physical twin and the digital twin, if commonality and reusability aspects are considered. The bold text in the table means that a new digital twin is created (both in its physical and digital definition).

In modular platform A the design is optimized individually, considering the alternative that satisfies the requirement of each customer segment at the lowest cost. This results in the two designs reused to satisfy customer 1 and customer 2. For these two designs, only the cost of manufacturing the physical definition is incurred (since the digital definition is reused instead). For customer segment 3, there is no available variant that satisfies the two requirements. Therefore, a new design needs to be manufactured and tested to be able to update the digital definition for future use. However, this has a significant impact on cost of the platform. In the simple cost model considered, the cost of a digital definition is considered to be double the cost of the physical counterpart.

In modular platform B, a different set of design decisions is made. To satisfy the three customer segments, it is decided to keep the same module 1 for all the three customers. This module is the one that satisfies the customer that requires the lowest capability (customer 1). To satisfy customer 2, module 1 is kept intact, while module 2 is modified creating a new variant ($b = 3200$ mm) which is manufactured and physically tested to update the digital definition. While this has a substantial increase in the cost (10.62 k€ in total), it provides a means to extend the prediction bandwidth capability of the platform. When experimenting with the updated digital definition with the higher forces requested by customer 3 (28,000 N) it can be noticed that the deflection remains within the given requirement (<50 mm). therefore, the same design can be reused for customer 3, and only the cost for manufacturing module 1 (0.48 k€) and module 2 (3.06 k€) is incurred.

This simple example highlights how Modular Platform B becomes more flexible than Modular Platform A in accommodating changes in requirements and customer demands, due to the benefits of sharing common physical and digital twin modules. The total platform cost of modular platform B is lower (15.4 k€ vs. 17.7 k€ of modular platform A). This analysis can suggest that it is worth on investing on the improvement of the prediction accuracy of modular platform B (which is lower than modular platform A), for example by collecting more datapoints or implementing more elaborated prediction algorithms.

3.6. Trading off predictive capability and digital twin costs: HET case study

One of the main requirements for a HET EPS is the Thrust (T). This case considers three customer segments and market applications and requirements (Table 3).

These customer segments are commercial companies that intend to acquire electric propulsion systems for the development of megaconstellations for worldwide internet coverage (Reid et al., 2016), where there is a need for these low-thrust but highly efficient systems. Also, there is a higher need to ensure that the designed EPS maintains the thrust within a certain tolerance, minimizing deviations and unique characteristics among the produced systems (Öhrwall Rönnbäck and Isaksson, 2018). This is because in the megaconstellation business the production volumes are going to dramatically increase, compared to traditional business based on a "one-off" production (Moore et al., 2021). Therefore, there is a higher risk that the thrust will not within an acceptable tolerance and will deviated between production series. Formulated as a requirement this is captured as a deviation tolerance from the nominal thrust (ΔT). From Table 3 it can be observed that customer 1 is less demanding in terms of thrust but more stringent in terms of deviation tolerance. This is dependent on a trade-off between the need for coverage and the launch cost incurred to introduce the satellites in orbit (Massey et al., 2020). The lower the altitude, the lower is the thrust required, yet the more satellites must be built to provide coverage (therefore, the higher the risk of deviation between the EPSs manufactured).

The objective for the manufacturers is to provide an EPS with a capability that meets all the requirements for the customer segments, while minimizing the total cost for the family of products to be manufactured to meet these requirements. The results for the requirements given by the three customer segments are summarized in Table 4.

The results show the reuse of the modules for four different modular platforms, considering the modules that satisfy the requirements of each customer segment. The modules are categorized as "reused" if the variant of a specific module is reused, "new" is the variant is developed as new. Also, the module is characterized as "failed" if the alternative does not fulfil at least one of the requirements. Also, the cost of the variants (both in terms of physical and digital twin) is visualized. The cost data is not shared, but only shown in relative comparison of the "mechanical FMS" taken as a reference. The results for the "mechanical FMS" show that, while this the most cost-effective modular platform, the requirements for the third customer segment are not satisfied. This is because of the low flow control range given by the thermothrottle (module 2). The thermothrottle module is not flexible enough to accommodate the different ranges of requirements given by the different customers. This is shown in Fig. 8. The figure displays the profiles of the response surface in the TU module for the thrust required by the three customer segments. These profiles are illustrated with black straight lines, which represent cross sections of the response surface. The grey areas around these cross sections represent statistical errors. This response surface represents the thrust at the varying of the mass flow rate ($\dot{m}$) and the voltage. Through desirability graphs (built into the JMP® statistical software) the required thrust and its tolerance can be set as desirability criteria (through a three-point selection, which is the yellow box in Fig. 8). This, in turn, gives the desirable values for the mass flow rate and the voltage to achieve those values (together with

Table 3
Requirement targets for the three customer segments.

Requirement	Customer Segment 1	Customer Segment 2	Customer Segment 3
Thrust (T)	10 mN	14 mN	18 mN
Thrust deviation tolerance (ΔT)	±1 mN	±2 mN	±3 mN

Table 4
Results of the different Modular Digital Twin Platform for the FMS case. The modules are categorized as "reused" if the variant of a specific module is reused, "new" is the variant is developed as new. Also, the module is characterized as "failed" if the alternative does not fulfil at least one of the requirements.

	Mechanical FMS			Bang bang FMS			Bang bang FMS - version 2			Proportional FMS		
Requirements	Cust. 1	Cust. 2	Cust. 3	Cust. 1	Cust. 2	Cust. 3	Cust. 1	Cust. 2	Cust. 3	Cust. 1	Cust. 2	Cust. 3
Thrust (T)	10 mN	14 mN	18 mN	10 mN	14 mN	18 mN	10 mN	14 mN	18 mN	10 mN	14 mN	18 mN
Thrust deviation tolerance (ΔT)	±1 mN	±2 mN	±3 mN	±1 mN	±2 mN	±3 mN	±1 mN	±2 mN	±3 mN	±1 mN	±2 mN	±3 mN
Module 1	Reused	Reused	**New**	**Failed**	**New**	Reused	Reused	**New**	Reused	Reused	**New**	Reused
Module 2	**New**	Reused	**Failed**	N/A	N/A	N/A	**New**	**New**	Reused	N/A	N/A	N/A
Costs												
Cost of Physical Definition (k€)	+0.0 %	+0.0 %	N/A	+0.0 %	+4.5 %	N/A	+3.0 %	+9.0 %	+0.0 %	+0.0 %	+8.0 %	+0.0 %
Cost of Digital Definition (k€)	+0.0 %	+0.0 %	N/A	+0.0 %	+9.0 %	N/A	+6.0 %	+18.0 %	+0.0 %	+0.0 %	+16.0 %	+0.0 %
Total Platform Cost (k€)	**+0.0 %**			**+13.5 %**			**+36.0 %**			**+24.0 %**		

their tolerance intervals). Considering only the FMS, the work on the digital twin definition is to predict whether the different modules of a platform possess the required capability. From Fig. 8, it can be observed that for customer 3 a mass flow rate of 1.2 mg/s needs to be obtained, which is outside the capability bandwidth provided by the mechanical FMS platform (the green lines in Fig. 8). This result is provided by the digital definition of the mechanical FMS platform (a response surface profiler similar to the one in Fig. 8. This response surface is not shown in this paper.

In has to be noted that the bandwith of this platform was already extended through the development of a new and mechanical valve and a new thermothrottle variant (Table 4). However, the requirement for customer 3 cannot be met, because of the intrinsic limitations of the chosen modular platform.

The second modular platform is a "bang-bang" FMS, where the themothrottle is not used (N/A as module 2). The result show that this platform is costlier than the "mechanical FMS". At the same time, the requirement for the customer 1 are not fulfilled. This is due to the low control resolution that is operated by the bang-bang system. In Fig. 8, this is shown by the red lines that represent the mass flow rate tolerance bandwidth of the "bang-bang" FMS. This bandwidth is given by the digital definition is this module (not shown in this paper). When matchinf this bandwidth with the required mass flow tolerance to achieve the required thrust tolerance (as defined by the desirability function, Fig. 8), it can be noticed that the tolerance is outside the range required to satisfy customer 1, because of the high instability of the flow of the bang-bang FMS.

To satisfy customer 1, an improvement to the bang-bang FMS can be made. This improvement is to introduce again the thermothrottle module as a mean to compensate the instability of the flow. This modular platform is named "bang-bang FMS – version 2″. The choice of this modular platform allows to satisfy all the three requirements; however it has a substantial impact on the overall cost of the platform, as new modules and variants need to be manufactured, tested and developed as digital twins.

The fourth alternative, the "Proportional FMS", allows to meet all the customer requirements. This is due to the ability of the proportional valve to operate with a precise control over a wide range of pressures and mass flow rates. This is displayed in Fig. 9, that illustrates the digital definition of the "proportional FMS" module. Here, the digital definition is represented by a regression model of 30 tests made on the proportional valve (Fig. 9-a), where the mass flow rate (in mg/s) is measured at the varying of the inlet pressure (in bar). Also, Fig. 9 displays the 'actual versus predicted plot' of the regression model of the mass flow rate. This plot works as a visual aid to also understand the accuracy of the model by relating observed (actual) values to predicted values. Ideally, the points should be close to the red diagonal line. The red band represents the confidence intervals. The blue line indicates the average. The coefficient of determination $R2 = 0.97$ (RSq in graph legend) indicate adequate accuracy of the model.

From the figure, it can be observed that for the ranges of mass flow rate needed to fulfill the customer requirements, the proportional-FMS has a strongly linear behavior, very little sensitive to variation. For higher mass flow rates, this variation increases, however still at acceptable levels. Therefore, this suggest that the proportional FMS can be used also for higher levels of mass flow rates. This point at the benefits of the proportional-FMS to be more flexible to accommodate more stringent customer requirements.

However, this implies an increase in the cost of the platform (as new variant for the proportional valve need to be developed). However, the cost of this platform is lower than the "bang-bang FMS – version 2″, which is the only other platform that can accommodate all the requirements of the three customer segments.

4. Discussion

In the electric propulsion system example, the approach enabled the comparison of different modular platform alternatives, systematically addressing the trade off between:

- the objectives of the individual products (finding the cheapest design that meets the customer requirements)
- the objectives of a product family, considering the ability of the design to extend the range of prediction for future designs, after "instantiation" as a digital definition.

The prediction accuracy capability, the accuracy of the digital twin and the total cost of the modular digital twin platform have been applied as "modularity drivers" (Erixon, 1998) to decide whether and when to develop a new digital twin module. A good candidate for a digital twin module is the one that enables to predict a large variety of capabilities with high accuracy at the minimal cost for the entire platform. Following these resulsts, the paper has focused on how to efficiently design digital twins in the early stages for design space exploration. This resonates well with flexibility literature (De Neufville and Scholtes, 2011) that suggests conceiving a system architecture with relatively low capability initially, but that allows for expansion if changes occur.

To perform the approach, some specific modelling methods have been used. For example, the EF-M representation was used, as it is a means for capturing interface and integration knowledge, especially in the case of integrated products (Raja et al., 2018). Completely modular designs are easier to decompose, in comparison to with integrated designs. EF-M can support in identifying the degree of independence of other parts in a design. However, the most appropriate methods to design a modular digital twin platform. These questions are left for future work. This paper has focused instead on the ways to which

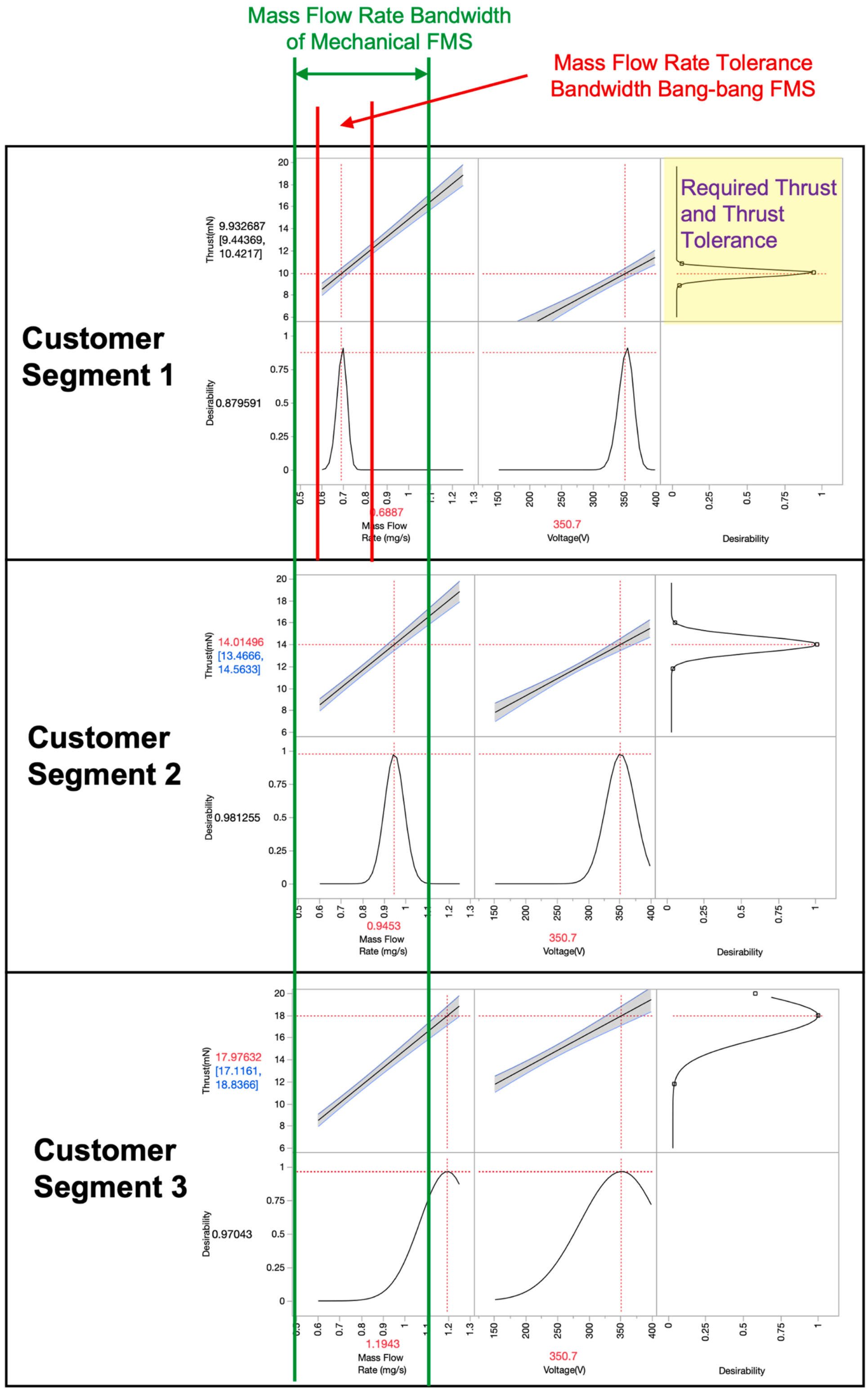

Fig. 8. Profiles of the response surface for optimizing the required thrust and thrust tolerance for the different customer segments. Image taken from JMP® prediction profiler.

alternative modular digital twin platforms can be modelled and compared (by defining key modularity drivers) to be used for design space exploration. However, more elaborated interface and integration knowledge is needed (Suh et al., 2010). Future work will focus on making a more articulated description of the dependencies among the digital twin modules in a design.

Other aspects of the proposed method also require further attention and future work. One issue is on combinatorial validity, i.e., how to ensure validity when combining modules. In this paper, this has been tackled using classical modularization strategies, which since a long time have used effectively to ensure combinatorial validity by the identification and control of a limited set of interfaces. It is further noted

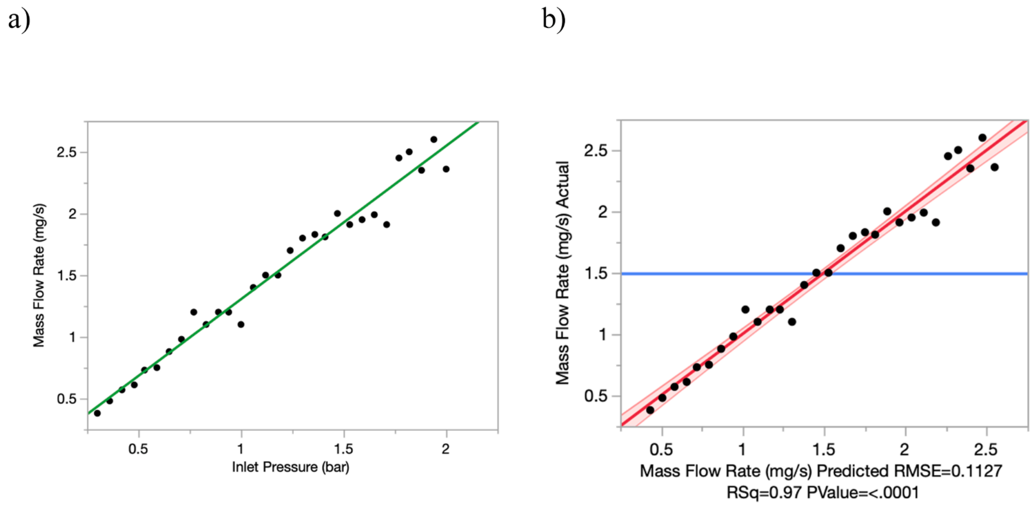

Fig. 9. Digital definition of the "proportional FMS" module.

that a digital platform twin relies on the existence of multiple designs (concepts) in the same design space. Validity of a predictive model, using digital twins, will likely improve with an increasing number of data points, yet complete validity is difficult to reach in practice.

5. Conclusion

This paper has proposed a cost-efficient approach to identify a set of trusted and robust *digital twin modules* that can be reused and recomposed to create digital twin variants, following a modular platform approach. Applying a modular approach to the creation digital twins can be effective and helpful in the earlier stages where the design can be largely changed, especially in the context of advanced systems such as aerospace and space products.

For this reason, the goal of this paper has been to provide a set of definitions and a method to design families of digital twins that are based on a modular platform principle. The method focuses on supporting designers in selecting the most appropriate mix of common and unique modules, as well as to determine the design targets for the unique modules. The application on the case study highlighted how the design of the modular platform has an impact on the cost of both the physical and the digital definition of a digital twin, if commonality and reusability aspects are considered.

The industrial partner in the case study, found the approach directly helpful in practice, especially since it directed focus on validity of early phase predictions and direct questions towards how to extract quantifiable information from physical tests for more general systems evaluation already in the design phases.

CRediT authorship contribution statement

Panarotto has independently planned and conducted the study over a period of one year, and structured and written the paper. Isaksson has contributed with experience and comments, and has written parts of the introduction, the discussion and conclusions. Vial has contributed with industrial experience and feedback.

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

The data that has been used is confidential.

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