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Towards Adopting Digital Twins to Support Design Reuse during Platform Concept Development

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Abstract (300-500 words)

To gain a first-mover advantage on the marketplace, manufacturers are striving to develop innovative products that meet the needs of a wide range of customers. Traditionally to support innovative design, the fuzzy concept stage has long been supported by heuristic design philosophies. In recent years, new supportive technologies have enabled concept generation based on the collection and reuse of existing data. Existing data can be collected from various sources; for example, customer reviews, historical data, or by studying existing products or other industrial assets such as production machines and tooling. Lately, the concept of Digital Twin (DT) has gained a wealth of attention as a means to construct a high-fidelity digital copy of a physical asset and to study its shape, position, gesture, status and motion. The common aim of the DT is to support the realistic model of system behavior that can support performance prediction and optimization. However, in providing sufficient support during the conceptual stages the realistic models become heavy and costly to adapt. While the emerging data-driven design approaches can be used to generate designs with alterations, there is a lack of support to generate and evaluate solutions during the conceptual stages. In this paper, a framework of a Digital Platform Twin (DPT) is proposed to fill this gap. In contrast to a sole high-fidelity digital representation, the DPT builds on abstracting multiple high-fidelity Digital Twins into a low-fidelity platform model, represented as a function model. The DPT framework proclaims the vision of supporting design engineers in the process of abstracting functionalities of existing assets, inserting new functionalities and technologies in the function structure to ultimately support the generation and evaluation of new functional concepts. To demonstrate the DPT framework, an automotive example is presented. We believe that design reuse can be enabled during platform concept development with the use of multiple DTs. To achieve this, a challenge is to practically realize the transcending in abstraction levels of the models: from Digital Twins to function model and from function model to geometry models. The transcending in abstraction levels is therefore a matter of future work.

Keywords: digital twin, platform-based design, conceptual development stages

1 Introduction

To gain advantages on the marketplace, manufacturers are striving to develop innovative products that meet the needs of a wide range of customers. To stay ahead of competitors, manufacturers must explore disruptive concepts (while at the same time conducting incremental improvements) for both their products as well as their production systems. For example, automotive companies incrementally improve the software of their existing cars and production equipment, while exploring new solutions to advance the hardware of their next generation cars and production systems. Incremental improvements are important to fine-tune existing assets; however, more innovative concepts that can be quickly integrated can move a company ahead of competitors.

The conceptual development stages are characterized by design freedom, yet constrained by uncertainty. At these stages exploration of new concepts can be conducted at low cost; however, little is known about the concepts to be developed. As a way to reduce the uncertainty posed during the conceptual stages, reuse of previously developed designs has proven to be useful (Khadilkar and Stauffer, 1996). To support reuse of previously developed designs in a context where the aim is to provide a variety of offerings to meet the needs of a wide range of customers, platform-based design has received a great deal of attention the last decades. Research on platform-based design suggest reuse of subsystems and interfaces (Meyer and Lehnerd, 1997), or reuse of company assets (Robertson and Ulrich, 1998). To achieve platform-based design the prerequisite of reuse is a common structure from which a stream of derivative products can be efficiently developed and produced.

In recent years, advances in data technologies have enabled reuse and concept generation based on a mass of existing data (Braha, 2013). In design, existing data can be collected from various sources; for example, customer reviews, historical data, or by studying existing products or other industrial assets such as production machines and tooling. Lately, the concept of Digital Twin (DT) has gained a wealth of attention as a means to construct a high-fidelity digital copy of a physical asset and to study its shape, position, gesture, status and motion. The common aim of the DT is to support the realistic model of system behavior that can support performance prediction and optimization To do so, a physical asset is linked with a virtual replica using sensor technologies (Glaessgen and Stargel, 2012). However, in providing sufficient support for reuse during the conceptual stages the realistic models become heavy and costly to adapt. While data-driven design approaches that have emerged can be used to generate designs with alterations, there is a lack of support to generate and evaluate innovative solutions.

The research presented in this paper was propelled by the following research question: *What are the main factors that enable design reuse during platform concept development adopting the concept of the Digital Twin?*

2 Method and Scope

The main aspects raised in this research are related to the ability to develop a variety of products and production systems in tandem to serve the needs of a multitude of customers. To do so, the use of theoretical concepts from platform-based design and the emerging paradigm of data-driven design is devised.

In literature, there is a vast body of knowledge related to the scoping of platforms, as well as detailed aspects of platform development, often related to parametric Computer Aided Design (CAD). However, these approaches often lack support during the conceptual stages before an embodiment of a design exist. While the input of the conceptual stages often is a mix of designers' visions, previously developed designs (in engineering mostly as CAD models or alike) and a broad range of collected data related to customer needs and market fluctuation, there is a lack of common structure among the data.

This paper uses a recognized approach for modeling platform concepts during the early development stages and propose a framework that proclaim that: by using Digital Twins as valuable sources of design data, structured design reuse among a set of products and production systems may be achieved (section 3). The framework is illustrated with an example from the automotive industry (section 4). The results and implications of the framework are discussed and concluded in section 5.

3 Literature Review

While developing a variety of products that can meet the needs of a multitude of customers, manufacturers strive to achieve commonality and distinctiveness of the product variants developed. A common approach to do so is to adopt a platform strategy (Meyer and Lehnerd, 1997) which is commonly achieved through modularizing the architecture of the product (Erixon et al., 1996) or the production system (Rogers and Bottaci, 1997). The aim of most platform strategies is to achieve economies of scale in production (Meyer et al., 2017) by sharing common components among a variety of product configurations and increasing the utilization of expensive production machines and tooling (Jiao et al., 2007). However, generating new concepts based on previously developed products is commonly lacking with conventional platform approaches (Alblas and Wortmann, 2014). To generate new concepts with the use of platforms, knowledge of previously developed designs needs to be represented and structured to be sufficiently reused.

3.1 Challenges of Reusing Knowledge and Data in Conceptual Design

New design solutions are typically generated based on creativity, combination, or modification (Tomiyama et al., 2009). For these different bases of generating new design solutions, the gist of supporting reuse of knowledge is a well sought ability. In fact, the conceptual stages pose great opportunity for reuse of knowledge (see Figure 1) across different functions of an organization, especially from downstream to upstream activities (Wheelwright and Clark, 1992) such as from production to product design and vice versa. Wang et al. (2002) identified that decision support tools that can give assistance to conceptual collaborative design are rare. Looking back, a wealth of approaches has been developed to support reuse of knowledge aiming at different development stages (Chandrasegaran et al., 2013) (see Figure 2). Several decades ago, design reuse that supported detailed design stages was enabled through for example Knowledge Based Engineering (KBE). KBE demonstrated powerful means to automatically generate and evaluate detailed designs and variations of products (La Rocca, 2012). However, in continuous workflows KBE approaches are typically stiff and rigid (Isaksson, 2003, Verhagen et al., 2012). Early applications of KBE were based on parametrization of geometry models in Computer Aided Design (CAD) software to reuse the geometries in order to automate routine design tasks (Chapman and Pinfold, 2001). Additional KBE applications aimed to support design engineers to understand 'what' to design, rather than just automating tedious routing work in design (Isaksson, 2003). More recent KBE application adopts both parametrized CAD geometries and combinatorial experimentation, allowing a larger design space to be evaluated and hence supporting the formation of new concepts (La Rocca, 2012).

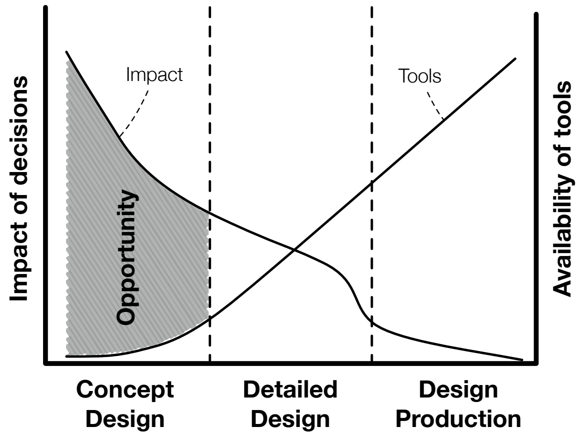

Figure 1. Collaborative design decision support tools aimed for the concept phases are rare (redrawn from Wang et al. (2002))

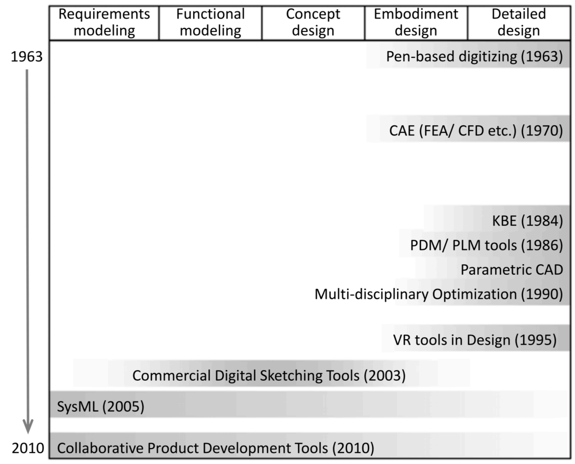

Figure 2. A mapping of tools that support reuse of knowledge during different development stages (Chandrasegaran et al., 2013)

In contrast to KBE, design reuse is not well supported in CAD during the conceptual stages (Deng et al., 2000). The CAD models are typically well-defined and have a pre-determined structure which is impractical to adapt, even if the geometry is parameterized. Therefore, other types of tools have emerged to improve reuse during the early stages of design, for example the systems engineering modeling language SysML (Friedenthal et al., 2014). SysML was developed specifically for specifying, analyzing, designing, and verifying complex systems during conceptual stages; however, capturing interconnections within the diagrams of SysML is difficult (Chandrasegaran et al., 2013).

A recent stream of research emerging from the application of data sciences to design (Braha, 2013) focus on the appealing idea of reusing data of previously developed products to identify novel design patterns for product families (Agard and Kusiak, 2004). Contemporary applications are for example extracting function knowledge from text (Cheong et al., 2017) and reviewing patents to explore new design opportunities (Song and Luo, 2017). While such approaches present high potential for supporting design exploration, they rely heavily on the ability to generalize the available dataset. The ability to generalize the dataset is challenged when the data mining algorithms are applied with the purpose of configuring a new platform with many variants (Romanowski and Nagi, 2004), because of the wide bandwidth of requirements that define the 'promising' design concepts (Li et al., 2015). This challenge is emphasized especially when data-mining algoritms are applied to identify new requirements which may not be captured in the existing dataset (Kang and Tucker, 2016). In tandem to these data-driven design approaches, a fast-emerging concept in both industry and research is the Digital Twin, that aim to mirror the life of an existing physical asset.

3.2 The Digital Twin as a Means to Mirror the Life of an Existing Physical Asset

The DT consists of three parts: the physical asset, the virtual asset, and the connected data that tie the physical and virtual asset (Glaessgen and Stargel, 2012). General Electric (GE) describes their industrial vision of the DT as a dynamic digital representation of an industrial asset that enables companies to better understand and predict the performance of their machines (GE, 2017). Authors at NASA believe that through the DT, ultra-high fidelity simulations that mirror the life of its twin may support the realistic study of system behavior (Glaessgen and Stargel, 2012). They also state that the heuristic design philosophies, physical testing and the common assumptions made to assimilate real operation will likely be inferior when addressing extreme requirements of the future. According to Tuegel et al. (2011), a DT can support better aircraft maintenance decisions made at the right time; however, one full DT model of an aircraft will require an “exaflop” (a billion billion calculations per second) in computational power to simulate real-time flight. This capability is projected to exist around 2022 (Tuegel et al., 2011). While the Digital Twin emerged as a concept for aerospace application it have now started to show promise also in and during production; however, there is a great deal of possibilities with the DT not yet explored (Negri et al., 2017). Schleich et al. (2017) propose shaping the Digital Twin for design and production engineering and discuss its implications on geometry assurance. On the same note, Söderberg et al. (2017) specifies and highlights the functionality and models needed to support real-time geometry assurance of products in individualized production.

Being the faithful mapping of the existing physical state, the DT can support the design stages by for example allowing a more transparent communication between users and design engineers; information that can be reused to support new design (Tao et al., 2017). At the same time, design engineers have the possibility to ‘mine’ the through-life data generated by the DT, in order to discover patterns and to gain insights about novel design concepts – ultimately enabling a wide exploration of the design space (West and Pyster, 2015). However, exploiting data in the context of design currently presents some limitations. In particular, the application of algortihms on the data generated from the digital twin could lead to the suggestion of incremental variation of the twin product, hence leading to sub-optimization (Bertoni et al., 2017). As an alternative, many physical prototypes (ranging from incremental to more radical concepts) could be generated to increase the available dataset for mining algorithms, but with the downside of increasing investment costs, and hence decreasing the actual benefit of creating a digital twin.

Grieves and Vickers (2017) identified a few obstacles of managing the DT data among and across organizational functions. A body of research on the Digital Twin concerns the integration of the DT into Product Lifecycle Management (PLM) (Abramovici et al., 2016). While PLM generally encompasses a wide range of engineering methods and processes, the product representations and information, as well as an adequate set of IT systems that needs to be considered and coordinated to support efficient product development (Stark, 2015), most PLM solutions today lack the flexibility needed to serve future customer needs. Abramovici et al. (2016) propose a solution that includes both digital product representations, as well as data collected along the product lifecycle. However, approaches that use design data related to products in use to form new concepts are rare. Tao et al. (2017) suggest a Digital Twin-driven product design and underline that their research is in the initial stage and that future work will concentrate on sensor technologies, DT data construction and management, and analysis methods based on the DT data. However, no clear direction is given on how to improve the support for design engineers when blending new customer needs and requirements with data of existing physical products currently in use. To do so, the DT must be conceptualized to an appropriate abstraction level suited for the conceptual stages.

3.3 From High-Fidelity Model to Low-Fidelity Model

To support design reuse during conceptual stages, the high-fidelity DT models must be prepared and abstracted into low-fidelity models. Schleich et al. (2017) introduce a reference model of an existing product to support the creation of low-fidelity, yet geometrical, model of the Digital Twin using Skin Model Shapes. However, to enable reuse during platform concept development, a sufficient representation scheme, or structure, of the envisioned variants is a necessity (Robertson and Ulrich, 1998, Chandrasegaran et al., 2013). The vast majority of research within engineering design and systems engineering advise functional modeling to create such a representation scheme.

Eckert (2013) performed an extensive interview study to map the use of functional modeling in industry. She found that design engineers in industry are prone to use functional modeling through conventional methods such as Quality Function Deployment (QFD) and Failure Mode and Effect Analysis (FMEA). However, these methods are mainly used to generate and structure requirements rather than to support design synthesis (Eckert, 2013). Xu et al. (2006) presented a function-based design synthesis approach by combining function-based information and computational design synthesis approaches. They state that the function-based product information modeling is critical to support the design synthesis. A way to represent function-based product information is through function-means (F-M) modeling, describing both requirements and solutions that support systematic function decomposition. An F-M model is a hierarchical model of a system that is decomposed into subordinate sub-systems. The F-M model was originally developed by (Tjalve, 1976) and (Andreasen, 1980). Analogous to the F-M models is axiomatic design, that suggests the zigzagging between functional requirements (FRs) and design parameters (DPs) The zigzagging points out the fact that a requirement cannot be decomposed into new FRs without identifying intermediate solutions (i.e. DPs) (Suh, 1990). Schachinger and Johannesson (2000) enhanced the function–means model by separating FRs from non-FRs, termed constraints (Cs). The E-FM tree has been frequently used to serve as a platform model (Claesson, 2006) supporting the platform development stages (Johannesson et al., 2017). More specifically, supporting platform concept development by means of functional modeling has been advised by for example Levandowski et al. (2014). A similar approach of abstracting an already manufactured design by sectioning the design and linking the sections to functions was proposed by Raja and Isaksson (2015); however, this method is highly manual.

4 Results

So far, research concerning the adoption of a DT-driven design approach has mostly focused on building Digital Twins (DTs) and managing the DT data in PLM systems (Tao et al., 2017) to support single product development (Tao et al., 2018). However, for manufacturing companies to be able to meet the needs of a wide range of customer needs, they sought to develop several generations of products and productions systems based on the same platform. To elevate the existing research and prepare for future research on the subject, there is a need to identify enabling factors that contribute to the effective use of the Digital Twin to support reuse of existing assets while adopting new customer needs and technologies.

This research proposes a framework to coordinate the data and information coming from variety of DTs in order to support platform concept development. The framework is proposed under the term Digital Platform Twin (DPT).

4.1 The Framework of the Digital Platform Twin

In Figure 3, the DPT is shown. Generally, data extracted from a variety of Digital Twins are devised to generate a variety of new designs. The DPT involves the transition through three states: (1) the existing physical state, (2) the digital state, and (3) the future physical state. The DPT can be regarded as one digital twin that mirror the low-fidelity aspects of the existing physical platform and the variants derived from it.

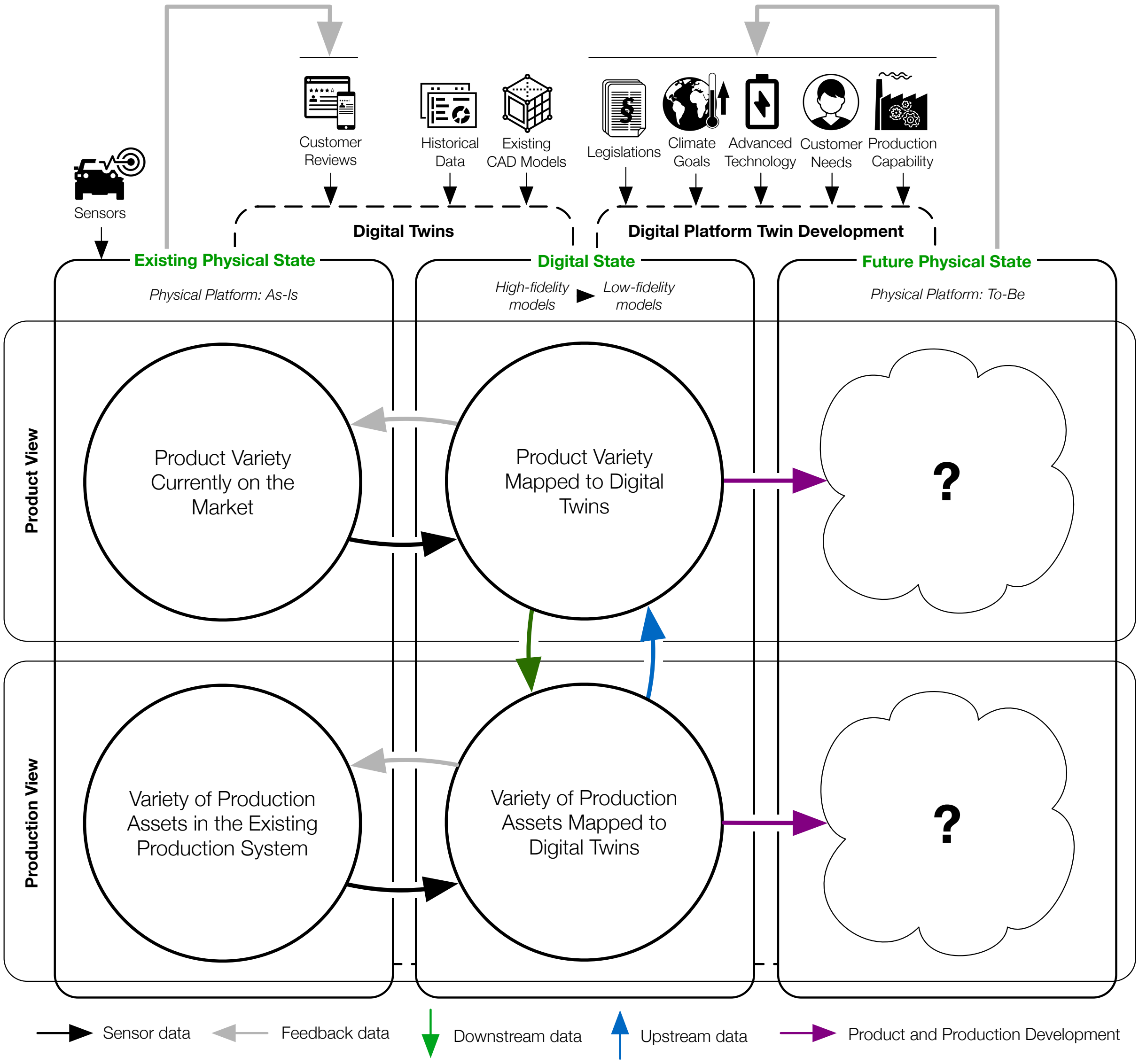

Figure 3. The framework of the Digital Platform Twin (DPT)

Much like applying the DT for the realistic model of product behavior, the DT is extensively applied in production (Negri et al., 2017). Therefore, both the product and production views and their interplay are parts of the DPT framework.

The *existing physical state* refers to the use and service phases of the existing physical platform; for example, the use and service of a family of cars, or the use and service of an arsenal of industrial robots with its tooling in production. During the use and service phases, the car variants and the industrial robots are decoupled, which is why there is no direct link across these.

The *digital state* refers to the construction of the digital twins as well as the managing of the corresponding data. The majority of the DT literature suggest that data is fed from sensors of the existing physical assets to high-fidelity simulation models of the digital state that are then fed back to for example optimize performance of the existing physical assets. Most DT approaches end there. This research elevates the notion of these approaches and elaborates on the envisioned future physical state and the corresponding development processes in-between the high-fidelity DT and the new customer needs and other stakeholder requirements that will be advanced into the next generation products and production systems.

The *future physical state* refers to the envisioned assets that will be derived from the DPT. The processes in the transition from the digital state to the future physical state. This transition includes the digital platform twin development from the existing DTs to the products and production systems of the future. During the early development stages, referred to as platform concept development, functional requirements (FRs) are formed and a set of alternative design solutions (DSs) that can solve each FR are created. In Figure 4, the process between the high-fidelity DTs and the low-fidelity function model (platform model) is highlighted. This process shows the need to abstract the high-fidelity DTs into the platform model. The process is organized in such a way that design reuse of the existing platform and its variants can be enabled. To form the function model, the variety of DTs are examined and abstracted as follows:

1) Functions of the DTs are identified and translated into Functional Requirements (FRs)
2) Design Solutions (DSs) of the DTs are identified and created
3) Redundant FRs and DSs among the variety of DTs are eliminated; thus, commonalities among the DTs are found
4) Links between FRs and DSs are then formed

Through steps 1-4, a common platform model of the existing physical state can be created. When a function model has been abstracted, representing a variety of Digital Twins, design engineers can use the common platform model to insert representations of new functionalities and technologies to ultimately support the generation and evaluation of new concepts that will have to prove feasible before entering the detail design stages. A process of platform preparation and execution is provided by Johannesson et al. (2017).

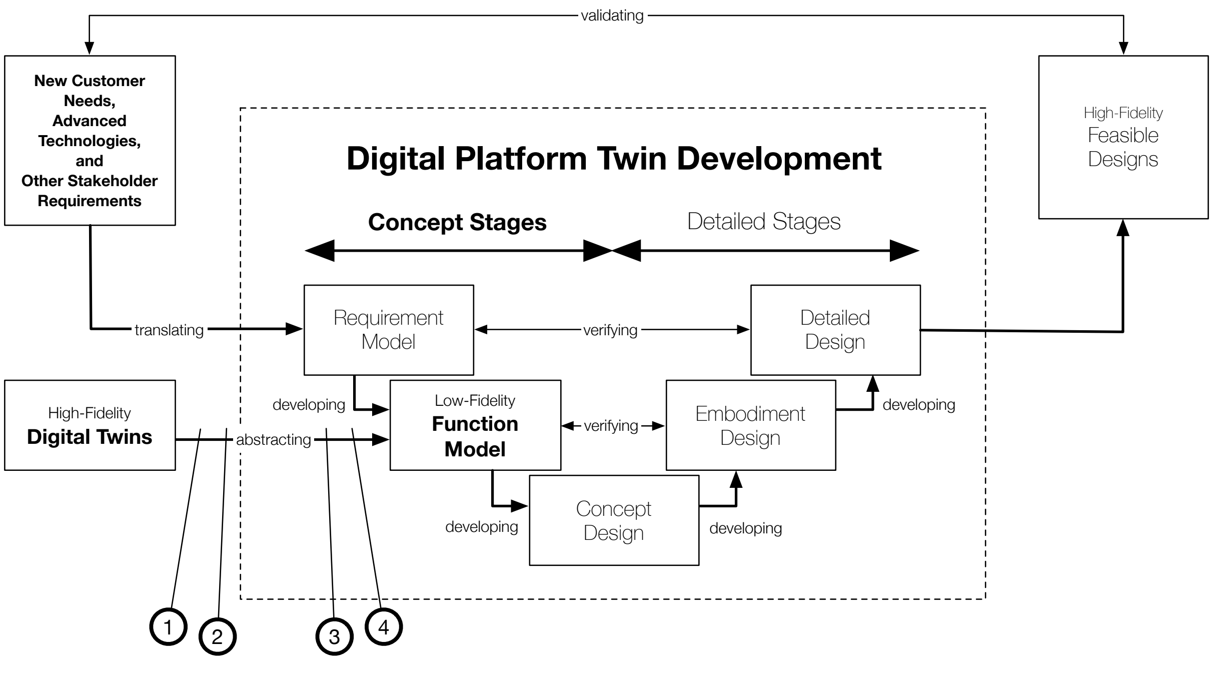

Figure 4. The 1-4 step process of abstracting the high-fidelity Digital Twins into a low-fidelity function model (platform model) may enable design reuse during platform concept development

5 Discussion and Conclusion

Literature poses benefits and challenges of the Digital Twin concept. Most research focuses on aspects that concern improving the ability to predict and optimize the performance of physical assets (GE, 2017, Grieves and Vickers, 2017), by means of for example (1) the realistic study of system behavior during the life of its physical twin (Glaessgen and Stargel, 2012), and (2) life cycle mapping and data integration (Tao et al., 2017, Tao et al., 2018). These approaches advocate the use of the DT as a high-fidelity model during single product development; however, the use of multiple DTs as a low-fidelity representation to support the conceptual design of multiple variants by means of platform-based design is unexplored.

For several reasons, the Digital Twin in its high-fidelity representation is insufficient to support platform concept development. The realistic models become heavy and costly to adapt when integrating new design solutions because of their pre-determined and detailed structure, even in the case of parameterized geometries. Although many data-driven design approaches based on impressive algorithms can support concept generation and design space exploration, these generated concepts typically lack innovative height.

In this paper, a Digital Platform Twin (DPT) framework is presented as a means to blend new customer needs and other stakeholder requirements with a reused platform model including its derivative variants. To create the platform model, multiple DTs needs to be conceptualized to an abstraction level close to customer voice. To simulate the appropriate abstraction level sought during the platform concept development, the use of function modeling techniques is proposed. Similar to the work of for example Levandowski et al. (2013) and Johannesson et al. (2017), the aim is to accelerate the adoption of new functionalities and technologies by modeling a function platform; yet, the DPT framework presented elevate these approaches and adopts multiple DTs to create the common platform model. The DPT can be regarded as one digital twin that mirror the low-fidelity aspects of the existing physical platform and the variants derived from it. Design reuse can be enabled by identifying the functions of the DTs, identifying and linking the corresponding design solutions of the DTs, and eliminating the redundant functions and design solutions among all the DTs. In this way a platform model of the existing physical state may be created. However, a main challenge of supporting design reuse during platform concept development adopting DTs is to transcend in abstraction levels: from physical assets to a common function model, and from the common function model to generate a variety of geometry models. This transcending in abstraction levels is a matter of future work.

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