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Product family design and optimization: a digital twin-enhanced approach

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Abstract

Complex product family design and optimization has been a major challenge in today's mass customization paradigm. Nevertheless, there is still no context-aware testbed to support it. Digital twin, as an emerging concept empowered by the cutting-edge information and communication technology, has been widely adopted to realize smart product-service systems across many sectors. Owing to its advantages of high-fidelity simulation and cyber-physical interconnectivity, a generic digital twin-driven approach is proposed to support the in-context virtual prototyping and usage condition monitoring of complex product family. A case study of tower crane family design and optimization is further exploited to validate its cost-effectiveness.

Keywords: Digital twin; product family design; design optimization; servitization

1. Main text

Mass customization, as a mature manufacturing paradigm, has been widely discussed for the past three decades [1]. It emphasizes on meeting individual customer needs by offering personalized solutions [2]. To achieve that, product family design and optimization play a significant role to enable the selection of customized attributes and also to overcome the paradox of higher variability and lower revenue [3]. Many effective approaches such as modular design [4], platform-based scalable design [5], design structure matrix [6] and adaptable design with open architecture product [7], have been brought up to-date. Nevertheless, despite those achievements, product family design and optimization are normally conducted separately, either from: 1) the very beginning of the conceptual design stage by adopting the mapping tools (e.g. quality function deployment) in-between the functional requirements and the design parameters; or 2) the reverse design during the usage stage by collecting essential feedback or information. Hence, there is no context-aware testbed to support product family design and optimization by considering both design and reverse design holistically through its lifecycle.

In today's industrial revolution towards Industrial 4.0, companies are ever increasingly leveraging the cutting-edge information and communication technologies (ICT) to realize the so-called smart product-service systems [8][9], by digitizing their physical resources (i.e. digitalization) in a smart, connected environment and also to offer high value-added services (i.e. servitization) as a solution bundle. Among those techniques, digital twin (DT) [10], as a critical component in this digital servitization era, mainly contains three parts: *"a) physical products in Real Space, b) virtual products in Virtual Space, and c) the connections of data and information that ties the virtual and real products together."* It aims to facilitate the high-fidelity simulation, monitoring, control and even prediction of the physical products throughout its lifecycle cost-effectively, enabled by the advanced cyber physical system [11]. Hence, it is assumed that DT may have high potentials to achieving the complex product family design and optimization holistically with context-awareness.

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Motivated by this, as an explorative study, this research proposes a generic DT-driven approach to support in-context complex product family design and optimization. The rest of the paper is organized as follows: Section 2 gives a brief review of related works. Section 3 describes the proposed approach for complex product family design and optimization. Section 4 further provides a case study of a tower crane family design to validate its cost-effectiveness. Section 5 summarizes the key findings of this research and highlights the future work.

2. Research Background

This section gives a brief review on the relevant works in the product family design and optimization, and digital twin-driven product design field recently.

2.1. Product family design and optimization

Product family design was defined as "*designing a set of products that share one or more common elements (e.g., components, modules, and subsystems)*" to satisfy various market applications [12]. As a major challenge in the mass customization paradigm, it has been largely discussed during the past decades especially in the market-driven approaches (e.g. QFD, functional modelling, etc.), and one may refer to [5][12][13] for more details. Meanwhile, recent studies have ever increasingly transformed into the data-driven clustering/ module partition approaches [14] [15] to predict the user preferences or functions, owing to the existence of large amount of data and rapid development of AI techniques.

Product family optimization, on the other hand, represents the change, upgrade and reconfiguration of existing product family during the usage stage [16]. Design structure matrix (DSM), as a classic engineering management approach has been widely adopted [17] with other AI techniques (e.g. bio-inspired algorithms) to enable minimized design propagations with redesign efficiency. Meanwhile, owing to the cutting-edge smart enabling technologies, DSM-based learning [18] and smart reconfiguration approach have been brought up [19] to close the design iteration cycles.

2.2. DT-driven product design

The DT concept was first conceived by Michael Grieves [20] in 2003 to provide an inexpensive method of investigating and evaluating complex systems in NASA rockets. Ever since then, many research works have been done in the DT-driven engineering lifecycle management field [21][22]. This work only selects the ones related to the product design stage, which can be summarized into three aspects:

1) *Geometry assurance*. Schleich et al. [23] proposed a comprehensive DT reference model hinged on the Skin Model Shapes concept for design geometry inspection. Biancolini and Cella [24] presented a mesh morphing workflow based on radial basis functions for geometric model validation via DT.

2) *Model-based design and simulation aspect*. Damjanovic-Behrendt and Behrendt [21] adopted the open source approach to design a DT demonstrator for high-fidelity simulation. Tao et al. [25] presented a DT-driven product design method with a bicycle design case study to assist in iterative redesign of existing products. Schluse et al. [26] combined DT with model-based systems engineering and simulation technology.

2) *Value co-creation (co-design) aspect*. Zheng et al. [9] introduced a DT-enabled co-design approach for smart wearable development. Meanwhile, they also presented a data-driven cyber-physical approach for engineering product co-development in the smart, connected environment [27].

Nevertheless, from existing literature, it can be found that existing works still treat product family design and optimization as two separate issues along the engineering lifecycle, and little work has been done to overcome the challenge of context-aware complex product family design and optimization holistically. To fill this gap, a novel DT-driven approach is proposed below.

3. Methodology

3.1. Tri-model for DT establishment

In our previous work [11], a systematic literature review was conducted and portrayed DT as *"a high fidelity virtual replica of the physical asset with real-time two-way communication for simulation purposes and decision-aiding features for product service enhancement"*. Hence, high-fidelity simulation, real-time bi-way communications, and data-driven decision-aiding capabilities are considered as the three key components of DT, as depicted in Fig. 1. In order to achieve a functional DT for complex product family design and optimization, three critical forms of data models are proposed below.

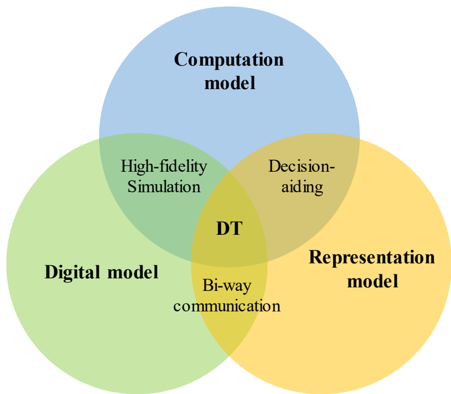

Fig. 1. Core components and data models for DT establishment.

Digital model. It is the high-fidelity modelling of the physical objects, which can be developed by using any existing CAD modelling software through external APIs. Nevertheless, in order to establish the DT, parametric modelling is preferred since it reduces the complexity in designing a system that interacts with other digital objects by means of numeric data. Hence, a reference model can be readily set-up with variations for product lifecycle management.

Representation model. In order to relate various product components, engineering constraints, and other data sources, data representation model should be established to maintain domain specific knowledge of product family. Meanwhile, massive data obtained from heterogenous sensors, digital models and ambient information require a well-established data exchange protocol (e.g. OPC UA) to ensure quality compilation, and NoSQL databases are crucial towards maintaining query efficiency and inferences.

Computation model. It performs data analytics and processing by leveraging the advanced AI techniques for product family optimization. DT provides a platform to combine the different analytical models together and integrate them into a single entity to perform more realistic analysis and evaluations on the physical objects.

Enabled by the abovementioned generic tri-models, complex product family design and optimization can be realized in a context-aware manner readily, as described below.

3.2. DT-driven product family design

As mentioned earlier, product family design often starts from the conceptual design stage, where requirements are mapped to the functional modules with corresponding design parameters determined afterwards. No graphical information of the physical objects has been provided yet. Nevertheless, DT can be leveraged to model the ambient information in the virtual environment, where product family design can be performed in a more user-friendly and visualized manner for idea generation. To summarize, it mainly facilitates design process from two aspects: 1) *benchmarking* and 2) *interacting*.

Benchmarking stands for the fact that ambient digital models creates a high-fidelity virtual environment to stimulate designers to create their own designs with functional constraints embedded (e.g. graphical, mechanical, etc.). For example, the DT of construction site ambience provides the essential information for tower crane product family design.

Interacting represents a higher-level of design process in today's smart, connected environment, where product family design should also consider the interaction with ambience as well [28]. Hence, instead of solely designing the physical components of the product family, the embedded hardware and software components should also be considered holistically. In such context, the designer should make the product family design compatible with the ambient objects, in an eco-system manner [9]. For instance, the graphical point cloud of city roads with real-time sensed road condition information from intelligent traffic facilities can be leveraged to design better unmanned vehicles in the virtual space.

3.3. DT-driven product family optimization

Product family optimization is normally conducted during the usage stage, where DT can be leveraged to facilitate it in two aspects: 1) reconfiguration and 2) reverse design.

Reconfiguration refers to the change or upgrade of configurable components of an existing product to meet new requirements [27]. It is enabled by the DT established between the physical instance and the cyber one, where configurable components, their adaptable interfaces and a set of constraints have been pre-defined. Hence, potential alternatives can be easily obtained from the existing product family based on product's self-awareness passively (e.g. prediction of remaining lifecycle) or user's own request actively.

Reverse design denotes the redesign of existing components/products based on its conditions in the context for design improvement or next-generation design purposes. DT undertakes the real-time monitoring of the critical components of the physical objects, where design optimization result can be further obtained based on the data model established. For instance, the user's in-context riding information can be leveraged [27] to optimize the parametric design of the bicycle.

4. Case study

As tower cranes are costly and require huge amount of manpower to function, selection of the tower crane is one of the tedious tasks as an erroneous selection could have huge financial implications. With tower crane rentals and manpower costs increasing, it is imperative that the selection phase is done quickly and properly. Project managers would typically contact a third-party crane distributor who would manually recommend a suitable tower crane based on experience. The process would take weeks as the third-party surveyor would have to physically view and understand the construction project scope. To tackle this challenge, based on our previous study [29], a tower crane DT solution is proposed to expedite the planning phase and the on-site usage phase.

4.1. DT establishment

The main functionalities of the tower crane DT are depicted in Fig. 2 based on the proposed tri-model approach, including 1) efficient 3D modelling of customized tower crane parts; 2) visualization and comparison of tower crane selection under various scenarios; and 3) using domain knowledge to form design optimization. To achieve these, the DT establishment is briefed as follows.

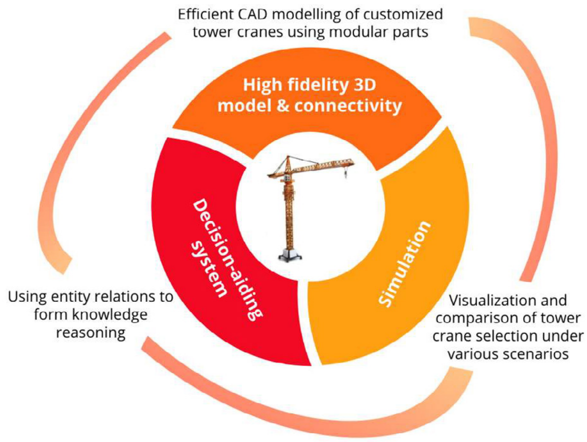

Fig. 2. Digital twin enabled approach to enhance product family design.

Digital model. In this case study, a point cloud mapping of an existing construction environment is held and mapped onto the simulation system. With the existing structural requirements known, identification of suitable areas for tower crane placement can take place and based on the construction requirements. Then, the physical models are designed with technical specifications obtained from Liebherr blueprints including the load range and maximum height and dimensions [30]. Using both 3DsMax and SolidWorks, the models are constructed with the product family methodology so that tower cranes within the same family would share the same tower crane section, as shown in Fig. 3.

Fig. 3. Simulation layout of the tower crane.

Representation model. Fig. 4 depicts a simplified ontology of a smart tower crane product family. The entities, attributes and their interrelationships provide the domain specific knowledge of the tower crane product family. Additional ontologies such as sensor specifications and crane specifications are then created separately and added to the existing ontology, with relations specified to provide a dynamic reusable system which is capable of adapting to different types of building scenarios. This ensures reliability and enables future models to be built on top of this platform to include a number of constructions use cases. Based on the specifications, the product has to be able to fulfill the essential protocols such as safety and lifting. Quality sensor data obtained is integrated into the ontology framework via a NoSQL graph database, where inconsistencies and ambiguous concepts can be reviewed to ensure accurate reflection of real-time conditions.

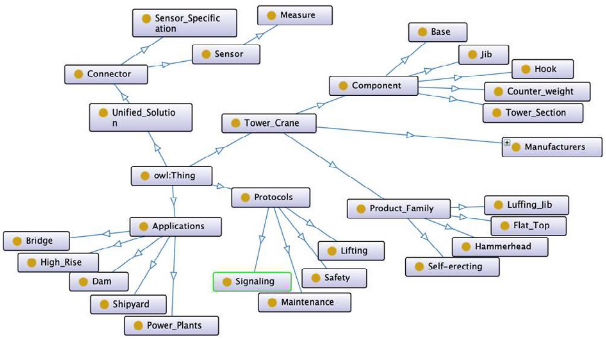

Fig. 4. Simplified structure of a generic tower crane ontology.

Computational model. Once the site parameters being derived from sensory data such as point cloud mapping or manual evaluation by an experienced project manager, the building information model (BIM) can be created for proper resource allocation for materials, equipment and manpower. After the procurement and installation phase, sensors embedded in the physical product can be translated onto the simulation program to achieve real-time monitoring and control with strict adherence to the various protocols.

4.2. DT-driven tower crane family design

As shown in Fig 3, the digital models of the construction site were also rendered to provide a visually realistic system mimicking actual conditions in the work site and imported as a .3ds file into the simulation system. Hence, specific crane built-up can then be configured, ensuring that the modular components are compatible and customized to fulfill the project requirements. This helps to save valuable time and cost in hiring the services of experienced third-party surveyors and takes into consideration possible adverse weather conditions with the aid of DT simulation.

4.3. DT-driven tower crane family optimization

During the course of construction, the DT established is capable of remote monitoring and controlling the slewing unit of the tower crane, as shown in Fig. 5. By leveraging the existing data representation model and computation model, predictive maintenance and timely change of its components can be made rather readily based on the real-time sensing data. Meanwhile, having a precise model would also enable operators to identify fault locations for maintenance work in the future. With embedded sensors monitoring not just the crane but also environmental factors such as visibility and wind speed, safety protocols such as safety distances can be activated with emergency protocols to halt lifting work in the event of unsuitable conditions. Therefore, this system ensures a speedier delivery and enforces safety standards effectively.

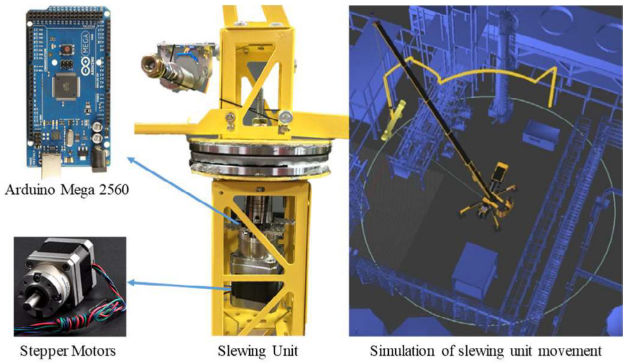

Fig. 5. An example of DT-driven bi-way communication of slewing unit.

5. Conclusion

Complex product family design and optimization has been a major challenge been discussed for years. To overcome the challenge of design/redesign with context-awareness, this paper proposes a generic DT-driven approach to support the in-context virtual prototyping and usage condition monitoring /control of complex product family. The scientific contribution of this study can be summarized as:

1) Proposed a tri-model based approach for DT establishment, including the digital model, representation model and computation model. These models interact with each other to provide the unique advantages of DT.

2)Introduced benchmarking and interacting mechanisms for DT-driven product family design at the early design stage.

3) Provided the redesign and reconfiguration mechanisms for DT-driven product family optimization at the usage stage.

A case study of a smart tower crane family design and optimization was further exploited to validate its cost-effectiveness. As an explorative study, it is suggested that future research can be done to introduce: 1) novel design theories for complex product family design in the smart, connected environment; 2) standardized interfaces for DT implementation in the design stage; and 3) self-adaptable approaches/algorithms for design with context-awareness.

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