EXPLORING THE POTENTIAL OF DIGITAL TWIN-DRIVEN DESIGN OF AERO-ENGINE STRUCTURES

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ABSTRACT

As the diversity of customer needs increases within the aerospace industry, so does the need for improved design practices to reduce quality issues downstream. When designing new products, design engineers struggle with applying tolerances to features, which often leads to expensive late design iterations. To mitigate this, one aerospace company is looking to reuse tolerance deviation data yielded during manufacturing in design. In the long term these data could provide the basis for a Digital Twin that can be used for improved product development. This article explores how data from production are used today, what issues prevents such data from being exploited in the design phase, and how they potentially could be used for design purposes in the future. To understand the current situation and identify the untapped potential of production data in design, an interview study was conducted in conjunction with a literature review. In this paper the current situation and primary barriers are presented and a possible path for further research and development is suggested.

Keywords: Digital Twin, Data-Driven Engineering, Design methodology, Industry 4.0, Design process

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Cite this article: Martinsson, J., Panarotto, M., Kokkolaras, M., Isaksson, O. (2021) 'Exploring the Potential of Digital Twin-Driven Design of Aero-Engine Structures', in *Proceedings of the International Conference on Engineering Design (ICED21),* Gothenburg, Sweden, 16-20 August 2021. DOI:10.1017/pds.2021.413

1 INTRODUCTION

Manufacturing companies in aerospace are often in the position where new, or derived, products need to be conceptualized for feasibility studies. Such effort needs to be quick and accurate when assessing the behavior of an innovative proposal. This requires the company to design for new conditions and requirements while ensuring manufacturability.

Most companies use a platform-based or modular design strategy for deriving product variants of an existing design already in production. If the product is considered novel, the technology has been tested in a pilot demonstration and validation study where prototypes are built. A new design is expected to inherit some degree of similarity to a known design as a means to minimize the risk of committing to a radically new development program.

Digital Twins (DTs) are an up and coming technology in the wake of "Industry 4.0" (Lu, 2017). They are increasingly used to make simulations and predictions on already existing products in production and in service (Tao, Zhang, *et al*., 2019). DTs are not directly applicable to novel designs since by definition a DT assumes the existence of a physical product.

The research presented in this paper explores means of utilizing data-driven engineering to make informed design decisions (Trauer *et al*., 2020; Provost & Fawcett, 2013). Such decisions might include the setting of design parameters, which tolerances to use, or deciding to avoid designs that are likely to encounter problems during production. Since the robustness of a design is primarily decided during the product development phase (Taguchi & Clausing, 1990), it is critical that these decisions are based on reliable information. The idea is to use existing production data of known products when evaluating new designs within the same product family (Jiao *et al*., 2007). While the new design would be of a similar architecture, size and functionality is expected to vary to some extent.

The proposition of using updated geometry from manufacturing in design is not new (Jeppsson & Svoboda, 1993). However, a thorough study of what is necessary to implement an infrastructure capable of facilitating data reuse, and what obstacles are in the way of such an implementation, is needed. Thus, the objective of this study is to investigate which data currently are being captured in production, and how it may be used for design purposes. Furthermore, in the light of recent advances of manufacturers using digital twins, this paper also aims to answer the question of whether digital twin technology can be used to facilitate such data reuse during the design phase.

2 LITERATURE REVIEW

A literature review was conducted on the topic of how manufacturing data and knowledge can be reused in product development. Additionally, a set of articles were explored to assert a definition of the DT concept, and to search for contemporary ideas for how DTs are, or can be, used during the design phase. In this section the results from the literature review has been summarized.

2.1 Use of production data and knowledge in product development

An early example of a feedback loop from production results to design can be found in Jeppsson and Svoboda, 1993. Jeppsson and Svoboda utilized an FE-simulation to obtain an early approximation of the final geometry of a component manufactured using hot isostatic pressing. By measuring the geometry of the physical component, their simulation model could be verified. If the geometry of the simulation model was different enough from the produced component, then the simulation model was updated to match the real physical results. However, even though the concept of reusing production data/knowledge in design has been present for many years, some issues appears to prevent industry from embracing the utilization of production data in design.

In an investigation of the aerospace industry by Souri *et al*., it was found that extracting historic manufacturing data and repurpose it for use in design often is very time-consuming, and that there is a need for a systematic approach (El Souri *et al*., 2019). In a literature review and case study conducted by Madrid *et al*., 2016 several barriers were identified that are preventing the use of production data for product development. Some examples include: the collected data are not suitable for use in design, the data are often outdated, the access to the data is limited and that the communication between design and manufacturing is lacking. The issue of providing suitable data, in other words *contextualized* data, from production to design is also discussed in an article released much earlier by

https://doi.org/10.1017/pds.2021.413 Published online by Cambridge University Press

Andersson and Isaksson, 2008 which implies that this problem of reusing manufacturing knowledge in design has persisted over time despite rigorous efforts to resolve the issue.

2.2 Use of digital twins in product development

A DT consists of three parts: a physical product, a virtual representation of that product, and the bi-directional connection between those entities (Jones *et al*., 2020; Kritzinger *et al*., 2018; Trauer, Schweigert-Recksiek, Engel, *et al*., 2020). The concept has seen a surge in popularity over the last decade (Jones *et al*., 2020; Tao *et al*., 2018; Wärmefjord *et al*., 2020), but the primary use-cases has not been for design, but rather for manufacturing, maintenance and service (Jones *et al*., 2020), which is also where it has seen the most implementation.

There is no specification of what a DT needs to encompass, as this changes depending on the use case. J Trauer *et al*., 2020 proposes dividing digital twins into three different subtypes - production twins, engineering twins, and operation twins, depending on the intended use case. A production twin would be intended for use in improving production results. An engineering twin is intended for use in product development and could for instance be used to optimize product features through simulation. An operation twin would focus on the product while it is in use. However, Trauer *et al*. 2020, also mentions that these categories have significant overlaps, as one DT could be interesting to more than a single discipline.

The notion of utilizing DTs for design has been proposed by several authors. Tao, Cheng, *et al*., 2018 highlighted its potential use in design and proposed the introduction of a "Virtual Verification" phase at the end of the design process, where the DT of a similar product is queried to verify a new design. F Tao *et al*., 2019 created a framework for utilizing DTs in product design where the previously mentioned virtual verification phase is utilized, whilst also highlighting the potential use of DTs for the development of similar products. Another suggested framework is the Digital Platform Twin (DPT), suggested by Landahl et al., 2018. The DPT utilizes DTs of multiple existing product variants of the same product platform to create an abstraction in the form of a function model. This function model can then be used to verify a new design, by ensuring that it fulfils the necessary functional requirements. The DPT is thus intended for use when developing new similar concepts that share the same platform.

Research has also been conducted on how DTs can be of use when designing geometrically robust products. Söderberg *et al*., 2017 suggests the use of DTs in design to assist in optimizing locating schemes to increase product robustness. The DT is to be created during the design phase, and could then potentially be reused by production for process control. Schleich *et al*., 2017 assisted in bridging the gap between design and manufacturing by creating a Digital Twin reference model for use in geometrical variation management.

Numerous issues with implementing DTs in industry has been identified. Wärmefjord *et al*., 2020 reports that, among other problems, companies tend not to update product models with real geometrical data, and that design engineers often lack access to production inspection data. Furthermore, as the concept of DT still is in its early stages there is no standardized way of how to model one (Tao, Zhang, *et al*., 2019).

3 INTERVIEW STUDY METHODOLOGY

The purpose of the interview study was to understand the current situation in industry, to explore which data are captured in production, and how such data potentially could be reused during the design phase.

A total of seven engineers were interviewed. These engineers were from different disciplines within the company, and had roles within production engineering, design engineering and management. See Table 1 for a list of the interviewees that includes which title the interviewee has at the company, how many years they have worked within the company, and which internal organization they belong to.

The interviews were conducted between June and August 2020 using a semi-structured approach (Blessing & Chakrabarti, 2009) with prepared questions. The questions were sent out to the participants, all of whom were employees at a Swedish aerospace manufacturing company, prior to the interviews such that they might prepare themselves if necessary. The topic of the interview was focused on which data are captured and stored from production, how these data are used, and how they might be of use for product development and design in the future. All participants were asked the same set of questions listed here:

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1. What is your role at the company?
2. Which production data are captured and stored at your company today?
3. How are these data captured in production stored?
4. What are the data captured in production primarily used for?
5. Are the data captured in production used in any capacity for product development?
6. How could the data captured in production be used for product development?
7. What are the most prevalent issues and obstacles that prevent the data captured in production from being used in product development?

Table 1. List of interviewees. Professional title, experience within aerospace (Ex. AS.), and which internal organization they belong to.

Title	Ex. AS.	Internal organization
Product Group Director	34yrs	Product Groups and Technology Implementation
Product Group Director	26yrs	Product Groups and Technology Implementation
Manufacturing Lead	29yrs	Global Technology Center
Technology Lead	19yrs	Global Technology Center
Process Engineer	14yrs	Global Technology Center
Manufacturing Lead	12yrs	Global Technology Center
Design Engineer	5yrs	Global Technology Center

4 INTERVIEW STUDY

In this section the answers from the semi-structured interview are summarized. The summaries have been separated into three parts. The first part handles issues described by engineers with setting the correct tolerances. This issue was brought up in all interviews, thus warranting its own section. The second part summarizes how the data are captured and stored. The third part summarizes what the interviewees thought of as the possibilities of utilizing production data for design, and the issues that prevents these possibilities from being implemented.

4.1 Problem with setting the correct geometric tolerances

Of primary concern is the issue of setting the correct tolerances when designing new features. Currently, it is common that tolerances are set too high during the design phase, which consequently forces the process to a halt once the design reaches production. In such situations the design needs to be re-worked. This is a costly and wasteful process since the changed design needs to be reverified. Conversely, tolerances are also at times set to values that are needlessly crude. While this usually does not lead to any issues in production, it might instead diminish the performance of the product. Thus, tolerance setting was perceived as critical for production both by design and production engineers.

4.2 Production data capture and storage

It was found that extensive amounts of data of various types are being recorded in production and stored in various databases. Some of these databases are centralized, while others are local and only available to a group of people. For the purposes of this study, geometric data are of primary concern.
There are essentially two types of geometric data. The first type is three-dimensional point cloud data, which is only used for some products. The second type is tolerance deviation data. These data takes the form of “deviation from the nominal value”, along with an ID number (see Figure 1). The nominal value cannot be extracted from these data, nor which feature was being processed, nor what material the process acted on. No such meta-data accompany the stored geometry tolerance deviation values.
The ID number known as a “Requirement ID” is the same ID found on the drafts of the product and is used to identify specific tolerance requirements. Thus, if the requirement ID is known then it is possible to manually look up which feature was processed. However, this is a cumbersome process as the drafts are stored as PDF-files, and thus the values within them are not indexed for search.
Currently, these data are primarily captured and used by production to assert the quality of the production system. Furthermore, all manufactured components are required by customers to have some degree of tracible measurement data. The data are rarely used directly for design, rather

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indirectly through quality reports or feedback exercises. Occasionally measurements are carried out for design during the production ramp-up phase to validate the robustness of new designs.

Figure 1. Tolerance deviation data structure.

4.3 The potential use of production data in design, and what prevents it from happening

The design engineers interviewed for this paper expressed the need for production data to improve their workflow. If design engineers knew the capability of production, then the risk of setting too narrow (or too crude) tolerances would be significantly reduced. As it stands today, setting tolerances on features either require the engineer to find the tolerancing of similar features that has been produced before, to guess, or to consult with an experienced production technician. Utilizing experienced production technicians appears to be the primary mechanic for knowledge reuse, along with "lessons learned"-documentation. However, historical tolerancing values and documentation from previous designs is sometimes unreliable since the manufacturing equipment changes, or is upgraded over time, thus also changing production capability. This issue is further amplified due to the vast time-gaps between new designs, which in some cases may stretch from 5-10 years. These time-gaps has limited many opportunities to reuse knowledge from previous iterations.

The most prevalent obstacle for utilizing the production data in design is their structure. The data are not accompanied by any meta-data which describes where the data comes from, which feature was being created, nor which material was utilized. If an engineer decides to use these data, that engineer also must manually correlate the requirement ID found on the draft to that in the database. This process is convoluted and time-consuming enough to ward off most engineers from attempting it. Those engineers that choose to go through this process will face further complications, as once the relevant dataset is located it can be quite hard to parse. The data are structured to be helpful for production, which may complicate contextualizing the data for the design engineers use case. Another less technical issue mentioned by some interviewees was the question of whether all design engineers knows the data exists. Since design engineers typically do not utilize the data, it is possible that a portion of them are unaware of the data's existence. As previously mentioned, a lot of data are stored in local networks, and might not be available to those outside it. According to some of the interviewees this is due to the conception that the data might not be interesting to other parts of the company, or because maintaining the infrastructure necessary to share the data is deemed too expensive. These data are thusly especially hard to find and utilize, however they might also be of less interest to design engineers due to such data's highly specific nature.

Furthermore, while the design department and the production department are both part of the same company, they are basically two different organizations. This further complicates solving the problem, since both organizations might have different internal goals, motivators, and cultures. One of the interviewed engineers suggested that due to the organization's "make to print" legacy, the production department might have developed a culture of keeping knowledge internally, resulting in a hampered implementation of feedback-loops back to design.

5 DISCUSSION: A VISION OF VIRTUAL EXTRAPOLATIONS OF SIMILAR PRODUCTS

During the interview study, the importance of up-to-date data and information being available to design engineers was frequently raised, which is in alignment with literature (Andersson & Isaksson, 2008; Madrid *et al.*, 2016; Söderberg *et al.*, 2017). One way of achieving such feedback can be to setup a DT of a product that is already being manufactured. This DT could then contain information

https://doi.org/10.1017/pds.2021.413 Published online by Cambridge University Press

about the actual geometry of the product, and the processes that has created it. Such a DT can be of use to production engineers when assessing and improving product quality or geometry assurance (Wärmefjord *et al*., 2020). However, since the DT closely mimics a physical product, and has predictive properties through simulation, then the same predictive methods can be applied to other, similar, product concepts in a design study. Such a design study may require extrapolated information from an existing DT to gain useful insights into the performance of similar products (see Figure 2). This extrapolation could then be queried by design engineers to assist in early decision making. The DT could thusly be thought of as an "Engineering Twin", or a "Production Twin" (Trauer, Schweigert-Recksiek, Engel, *et al*., 2020) due to its application in both product development and production. While such a DT might not have as strong predictive properties as a DT calibrated to mirror an existing physical counterpart, its predictions could still be useful. One example is a design study of a typical engine frame with vanes, where the number of vanes and their lean angles are varied. The manufacturing costs derived from weld operations need to be assessed together with performance parameters such as its mechanical load bearing behaviour. The impact of weld parameters on time and cost are simulated in the DT (see Figure 3).

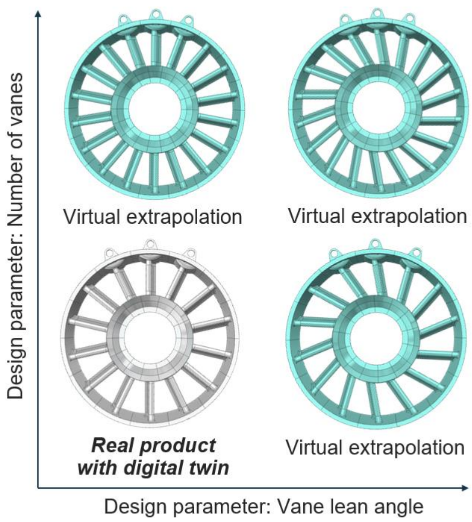

Figure 2. Illustration of virtual extrapolations of similar products.

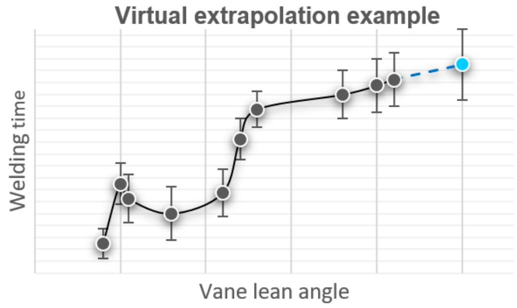

Figure 3. The cyan point represents a virtual extrapolation. The grey points represent Digital Twins. The vertical lines represent variation.

Naturally, the leap from having unstructured data to a fully functional digital twin is considerably vast. The development would need to be cumulative. The first milestone could be to create a digital model which is manually updated, which then could evolve into a digital shadow, where the virtual entity is automatically updated, and finally into a digital twin.

6 CONCLUSION

The objective of this study has been to investigate what data is captured in production, and how it may be used for the purposes of design. The conducted interviews indicate that there is indeed a need for design engineers to extract tolerance data from existing products in order to properly set tolerances for new designs. Thus, designs that has historically proven to be problematic, or currently are hard to

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manufacture, can be avoided. Such data might also assist engineers in creating more robust designs, that are less sensitive to geometric variation. If the design engineers were to be granted a means for utilizing production data, costly design iterations could be avoided. These design iterations are costly because changes in design requires it to be reverified. The changes might also warrant another iteration through production preparation if the geometry has been significantly altered. Figure 4 illustrates this concept using generic processes based on (Ulrich & Eppinger, 2012).

As mentioned during the interviews, at least two mechanisms for transferring production feedback to design are already in place. Specifically, "lessons learned"-documentation and the consultation of experienced production technicians. However, these methods are often time-consuming and sometimes inaccurate due to the time-gap between new designs. The utilization of production data would enable design engineers to take advantage of the latest available information.

Based on the results of the interview study, three obstacles were identified that prevents production knowledge and data from being utilized in design. These obstacles are:

1. *Extracting relevant production data is time-consuming.*
2. *Production data are not contextualized for use in design.*
3. *Design and Manufacturing are two separate organizations with divergent priorities.*

It could be argued that the first two listed obstacles are two sides of the same coin, since if the data were contextualized for design it would likely be less time-consuming to extract.

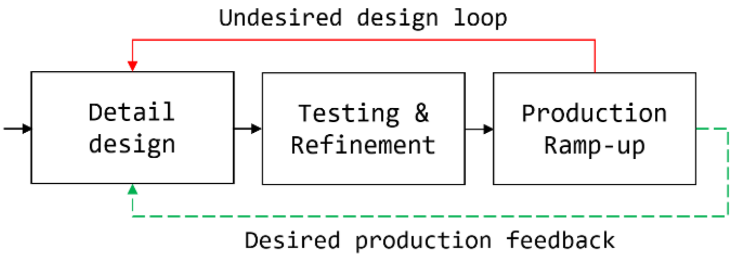

Figure 4. Illustration of an undesired re-design loop, and the desired production-design feedback loop.

To make it more feasible to utilize the data for design, the data needs to be restructured into a format that can be understood by design engineers. As the interviews indicate, the data are hard to contextualize. This was affirmed both in literature, as well as in the interviews. A solution to this issue could possibly be to incorporate more meta-data into the deviation data structure such as what feature was being processed, which product that part belongs to, what machine was doing the processing, and what the nominal value was. The principle of providing appropriate meta-data should also be extended to drafts and material certificates, which are currently stored as PDFs. Drafts could, for instance, be tagged with meta-data that specifies what product it belongs to, what materials it utilizes, what features it contains and what the operation list looks like. Material certificates could be provided with an ID that allows other data entries to refer to a specific material. For instance, geometry deviation data could specify which material was being processed at the time. Granted structures as described, it would be possible to quickly poll the database for all relevant information without having to manually search for the individual data components.

Furthermore, since design and manufacturing are two different organizations, chances for change to occur increases if both organizations have something to gain. Implementing a system for reusing production data in design requires a significant effort both from the production organization, and the design organization. The production organization would likely be required to rethink how the data are structured such that it can be used by themselves, and design. On the other hand, the design organization would need to review their methodology to incorporate the use of production data. If these changes were to occur, then it could benefit both organizations. Knowledge of production capability in design could potentially result in an improvement to production performance, as such knowledge might lead to more appropriate tolerancing. The design organization could potentially see a significant reduction to waste in the form of re-work, as less time would be spent conducting re-design loops.

ACKNOWLEDGEMENTS

This research is supported by Sweden's Innovation Agency (VINNOVA) through the NFFP7 program.

REFERENCES

Andersson, P., & Isaksson, O. (2008). Manufacturing system to support design concept and reuse of manufacturing experience. In M. Mitsuishi, K. Ueda, & F. Kimura (Eds.), Manufacturing Systems and Technologies for the New Frontier (pp. 137–140). Springer London. https://doi.org/10.1007/978-1-84800-267-8_28

Blessing, L. T. M., & Chakrabarti, A. (2009). DRM: A Design Reseach Methodology. In DRM, a Design Research Methodology. Springer. https://doi.org/10.1007/978-1-84882-587-1_2

El Souri, M., Gao, J., & Simmonds, C. (2019). Integrating manufacturing knowledge with design process to improve quality in the aerospace industry. Procedia CIRP, 84, 374–379. https://doi.org/10.1016/j.procir.2019.04.179

Jeppsson, P., & Svoboda, A. (1993). Integrated Design and Verification System for Finite Element Modelling. Concurrent Engineering, 1(4), 213–217. https://doi.org/10.1177/1063293X9300100404

Jiao, J., Simpson, T. W., & Siddique, Z. (2007). Guest Editorial: Product family design and platform-based product development. Journal of Intelligent Manufacturing, 18(1), 1–3. https://doi.org/10.1007/s10845-007-0001-4

Jones, D., Snider, C., Nassehi, A., Yon, J., & Hicks, B. (2020). Characterising the Digital Twin: A systematic literature review. CIRP Journal of Manufacturing Science and Technology, 29, 36–52. https://doi.org/10.1016/j.cirpj.2020.02.002

Kritzinger, W., Karner, M., Traar, G., Henjes, J., & Sihn, W. (2018). Digital Twin in manufacturing: A categorical literature review and classification. IFAC-PapersOnLine, 51(11), 1016–1022. https://doi.org/10.1016/j.ifacol.2018.08.474

Landahl, J., Panarotto, M., Johannesson, H., Isaksson, O., & Lööf, J. (2018). Towards adopting digital twins to support design reuse during platform concept development. Proceedings of NordDesign: Design in the Era of Digitalization, NordDesign 2018.

Lu, Y. (2017). Industry 4.0: A survey on technologies, applications and open research issues. Journal of Industrial Information Integration, 6, 1–10. https://doi.org/10.1016/j.jii.2017.04.005

Madrid, J., Vallhagen, J., Söderberg, R., & Wärmefjord, K. (2016). Enabling Reuse of Inspection Data to Support Robust Design: A Case in the Aerospace Industry. Procedia CIRP, 43, 41–46. https://doi.org/10.1016/j.procir.2016.02.137

Provost, F., & Fawcett, T. (2013). Data Science and its Relationship to Big Data and Data-Driven Decision Making. Big Data, 1(1), 51–59. https://doi.org/10.1089/big.2013.1508

Schleich, B., Anwer, N., Mathieu, L., & Wartzack, S. (2017). Shaping the digital twin for design and production engineering. CIRP Annals - Manufacturing Technology, 66(1), 141–144. https://doi.org/10.1016/j.cirp.2017.04.040

Söderberg, R., Wärmefjord, K., Carlson, J. S., & Lindkvist, L. (2017). Toward a Digital Twin for real-time geometry assurance in individualized production. CIRP Annals - Manufacturing Technology, 66(1), 137–140. https://doi.org/10.1016/j.cirp.2017.04.038

Taguchi, G., & Clausing, D. (1990). Robust quality. Harvard Business Review, 68(1), 65–75.

Tao, F., Cheng, J., Qi, Q., Zhang, M., Zhang, H., & Sui, F. (2018). Digital twin-driven product design, manufacturing and service with big data. International Journal of Advanced Manufacturing Technology, 94(9–12), 3563–3576. https://doi.org/10.1007/s00170-017-0233-1

Tao, F., Sui, F., Liu, A., Qi, Q., Zhang, M., Song, B., Guo, Z., Lu, S. C. Y., & Nee, A. Y. C. (2019). Digital twin-driven product design framework. International Journal of Production Research, 57(12), 3935–3953. https://doi.org/10.1080/00207543.2018.1443229

Tao, F., Zhang, H., Liu, A., & Nee, A. Y. C. (2019). Digital Twin in Industry: State-of-the-Art. IEEE Transactions on Industrial Informatics, 15(4), 2405–2415. https://doi.org/10.1109/TII.2018.2873186

Trauer, J., Schweigert-Recksiek, S., Engel, C., Spreitzer, K., & Zimmermann, M. (2020). What Is a Digital Twin? – Definitions and Insights From an Industrial Case Study in Technical Product Development. Proceedings of the Design Society: DESIGN Conference, 1, 757–766. https://doi.org/10.1017/dsd.2020.15

Trauer, J., Schweigert-Recksiek, S., Okamoto, L. O., Spreitzer, K., Mörtl, M., & Zimmermann, M. (2020). Data-driven engineering definitions and insights from an industrial case study for a new approach in technical product development. Proceedings of the NordDesign 2020 Conference, NordDesign 2020, 1–12. https://doi.org/10.35199/norddesign2020.46

Ulrich, K. T., & Eppinger, S. D. (2012). Product design and development. McGraw-Hill/Irwin.

Wärmefjord, K., Söderberg, R., Schleich, B., & Wang, H. (2020). Digital twin for variation management: A general framework and identification of industrial challenges related to the implementation. Applied Sciences (Switzerland), 10(10), 3342. https://doi.org/10.3390/APP10103342