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Research Article

A Comparative Study of Digital Twin and Additively Manufactured Laboratory Model Slider–Crank Mechanisms

Mr. Michael Ricketts,[1] Dr. Samson Oloketuyi,[2]

[1] Physical Science Department, School of Science, Yabatech College of Technology 1;
[2] Department of Industrial Maintenance Engineering, Yaba College of Technology2;

Corresponding Author: Michael.ricketts@yabatech.edu.ng

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Abstract

The slider–crank mechanism (SCM) is one of the most widely used mechanical systems for converting rotary motion into linear motion in engineering applications such as internal combustion engines, compressors, and pumping systems. In recent years, digital twin technology has emerged as a powerful tool for modelling and analysing the behaviour of physical systems in a virtual environment. This study presents the development and validation of a digital twin model of a slider–crank mechanism and its comparison with a fabricated physical prototype produced using additive manufacturing techniques. The kinematic behaviour of the mechanism was modelled using the classical formulation proposed by Ivan Ivanovich Artobolevsky for slider–crank mechanisms. The mathematical model was implemented in the Python programming environment to create a digital twin capable of simulating the motion of the system. The graphical representation and animation of the mechanism were developed using the Python Turtle Graphics Library, while the graphical user interface was implemented using Tkinter to allow user interaction with the model parameters such as crank radius, connecting rod length, and crank rotation angle. To validate the digital twin, a physical slider–crank mechanism prototype was designed using 3D computer-aided design (CAD) software and fabricated using PETG filament on an Anycubic Kobra S1 3D printer. The crank radius and connecting rod length were set to 40 mm and 108 mm, respectively. Experimental measurements of slider displacement were obtained by rotating the crank from 0° to 360° at regular angular intervals and recording the corresponding slider motion. The displacement data from both the digital twin and the physical prototype were observed to know the slider movement in terms of displacement, velocity, and acceleration. On the other hand, a check of how closely the digital model matches the real system, comparative plots were generated and simple error analyses were carried out. From the results, it is clear that there is a good level of agreement between the two, with an average percentage error of 4.3%. These differences can reasonably be linked to factors such as fabrication tolerances, friction within the system, and possible measurement errors. Overall, the study shows that the developed digital twin approach can be used as a practical and reliable tool for studying the kinematic behaviour of slider–crank mechanisms, with useful applications in teaching, design work, and experimental validation.

Keywords

* Corresponding Author:
Mr Michael Ricketts, Physical Science Department, School of Science, Yabatech College of Technology, Michael.ricketts@yabatech.edu.ng;
Tel.: +234 802 213 6299

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Slider-crank, Mechanism, Digital-twin, Graphic Library, Python, Prototype

Introduction

This research was motivated by our desire to take advantage of the synergy between additive manufacturing (AM) and digital twin (DT) technologies. The relationship between these two technologies has significantly improved the way mechanical systems are designed and developed, making it possible to create complex systems that were previously difficult to realize. In particular, 3D printing allows for rapid iteration and customization—tasks that were once tedious and time-consuming when using traditional subtractive manufacturing methods [1, 2].

With the availability of high-speed computing, our interest in digital twin technology has grown. What was once a specialized tool used mainly in aerospace and industrial applications has now evolved into a widely adopted approach for system analysis and monitoring [3]. A digital twin is generally understood as a virtual representation of a physical system, where both share similar characteristics. By continuously updating the digital model with information from its physical counterpart, it becomes possible to carry out real-time analysis, diagnostics, and even predictive assessments [4]. In our view, this capability has strong potential to address the challenge of limited laboratory equipment in schools, particularly in developing countries, if properly adapted for virtual laboratory applications.

It is important to emphasize that the implementation of digital twin technology can vary widely in complexity. In this work, we adopt a simplified approach suitable for educational purposes. Here, the digital twin is not intended to be a highly detailed multi-physics model, but rather a functional representation that helps in understanding the core kinematic behavior of a mechanism [5].

Our approach is therefore to examine the digital twin concept from an educational perspective by carrying out a comparative study between a manually operated, additively manufactured slider-crank mechanism and its digital twin developed using the Python Turtle graphics library. The slider-crank mechanism was chosen because of its fundamental role in converting rotary motion into reciprocating motion. Its kinematic behavior is well understood, and it is widely used in engineering applications, ranging from internal combustion engines to automated industrial machines [6].

In fabricating the mechanism using low-cost fused deposition modelling (FDM), we intentionally introduce real-world factors into the system. These include geometric inaccuracies from the printing process, layer-dependent material behavior, and variations in joint friction—factors that are often ignored in ideal textbook models [7, 8]. In teaching, we frequently assume ideal conditions, but in practice, these assumptions lead to noticeable differences between theoretical predictions and actual performance.

We also observe that recent developments have made digital twin technology more accessible, moving away from expensive industrial software toward open-source and educational tools. The Python programming platform, in particular, has gained attention due to its flexibility, rich set of libraries, and ease of use [9]. Libraries such as Tkinter and Turtle, although originally designed for basic graphics programming, are now being applied in the visualization of engineering systems.

In this study, we make use of the Turtle graphics library to animate the motion of the slider-crank mechanism based on its kinematic relationships. While Turtle is not as advanced as tools used for finite element analysis or multi-body dynamics, it is sufficiently capable of predicting position, velocity, and acceleration with reasonable accuracy. This makes it suitable for what can be described as “lightweight” digital twins, where the focus is on understanding system behavior rather than achieving perfect physical representation [10].

Another important aspect of this work is the manual operation of the physical mechanism. This allows us to directly compare the observed motion with the simulated results. Unlike industrial digital twin systems that rely on sensors such as encoders and accelerometers for synchronization [11], our approach uses the human operator as the input source, with comparison carried out visually rather than through automated data acquisition.

This study is positioned within the emerging area of human-in-the-loop digital twinning, particularly in an educational context. While existing research has focused on the properties of 3D-printed components [12, 13] and the theoretical development of digital twin systems [14], there is limited work that combines low-cost additive manufacturing, manual operation, and simple code-based simulations.

From our review of the literature, it is also evident that there is a need for more practical case studies that explore digital twin applications outside high-cost industrial environments. For example, studies by Jones et al. (2020) and Van der Horn and Mahadevan (2021) highlight this gap [3, 4]. In addition, the use of the Python

* Corresponding Author:
Mr Michael Ricketts, Physical Science Department, School of Science, Yabatech College of Technology, Michael.ricketts@yabatech.edu.ng;
Tel.: +234 802 213 6299

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Turtle library for simulating mechanism kinematics and comparing it with a physical 3D-printed model has not been widely reported in peer-reviewed research.

This work therefore aims to fill this gap by presenting a clear methodology and comparative analysis of a manually operated, 3D-printed slider-crank mechanism and its digital twin. The objectives of the study are to:

1. Evaluate how well a simplified Python Turtle simulation can replicate the kinematic behavior of a physical mechanism.
2. Identify the differences introduced by manual operation and manufacturing imperfections, such as joint clearance and friction.
3. Demonstrate the educational value of this approach in helping students understand both mechanism behavior and the basic concept of digital twinning.

Ultimately, this research provides a practical framework for developing and assessing simplified digital twins for additively manufactured systems. It is particularly relevant for engineering education in developing countries, such as Nigeria, where access to advanced laboratory equipment is limited, and cost-effective alternatives are essential.

Materials and methods

2.1 Development of the Digital Twin Slider–Crank Mechanism

A python program was developed by using the mathematical equation 1.0 developed by Artobolevsky for both inline and off-set slider crank mechanism. Figure 1.0 was produced by computer aided drawing to represent the general form of slider crank mechanism suitable for both inline and off-set models. The coordinates of notable points of the mechanisms were identified and recorded in order to map them to a Python-based simulation environment. The notable points so identified are crank centre, connecting rod joints and slider position to allow accurate program development.

In the Python program, the graphic model of the mechanism was drawn by using the turtle library; this enhances real-time visualization of the mechanism motion. This library is easy to use for simple graphic development. The graphical user interface (GUI) was developed by adopting Tkinter library to allow easy way to interact with the program.

The interface enables users to input the essential parameters of the SCM; the following are to be inputted: crank radius (mm), Connecting rod length (mm), Crank rotation angle (degrees). The slider displacement is measured both digitally and in analog form. The digital output is indicated in a text box while the analog output of the slider from the top dead centre (TDC) is measured on a linear scale included in the Python program. The digital twin (SCM) was used to perform an experiment; the crank was rotated from 0 to 360 at intervals of 30 and the slider displacements from the TDC were recorded for further analysis.

2.2 Design and Fabrication of the Physical Prototype

A physical prototype of the SCM was designed using 3D CAD software (FreeCAD v.1.1.1). The geometric parameters used for fabrication were: crank radius: 40 mm and connecting rod length: 108 mm

All structural components of the mechanism were fabricated using (polyethylene terephthalate glycol-modified) PETG filament on an Anycubic Kobra S1 3D printer. The crank protractor and linear displacement scale were manufactured by using a laser cutting/engraving machine to ensure dimensional accuracy and readability. After fabrication, all components were assembled to form a functional slider–crank mechanism. Care was taken to ensure proper alignment of joints and smooth translational motion of the slider.

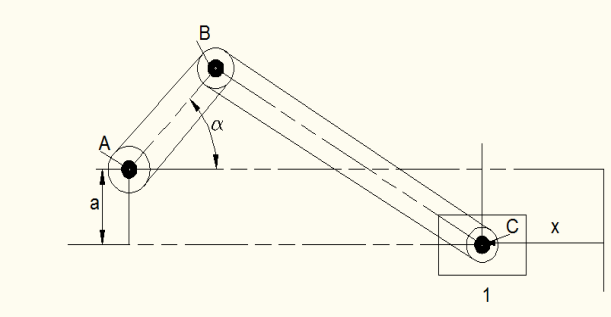


Figure 1.0 Slider Crank Mechanism

According to Artobolesky, the displacement of slider 1 from its right-hand extreme (dead centre) position is

$$x = \sqrt{(AB+BC)^2 - a^2} - AB\cos\alpha - BC\sqrt{1-\left(\frac{AB\sin\alpha + a}{BC}\right)^2} \quad 1.0$$

Where a= offset

α=angle of rotation of crank AB

2.3 Experimental Procedure

Two sets of experiments were conducted:

2.3.1 Digital Experiment – Using the Python-based digital twin, crank rotation was varied from 0° to 360° in 30° increments. Slider displacement values were recorded at each angular position.

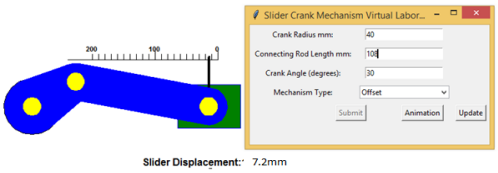


Figure 2.0 Slider crank mechanism digital twin

2.3.2 Physical Experiment – The fabricated prototype was manually rotated through the same angular positions (0°–360° at 30° intervals). The crank angle was measured using the mounted protractor, while slider displacement was measured using the linear scale attached to the mechanism.



Figure 3.0 3D printed slider crank mechanism

2.4 Data Processing and Kinematic Analysis

The displacement data obtained from both the digital twin and the fabricated prototype were compiled for analysis. The slider velocity and acceleration were calculated using numerical differentiation of the displacement data with respect to the crank angle.

The kinematic quantities evaluated include:

Slider displacement x

Slider velocity $$v = \omega \frac{dx}{d\alpha} \qquad 2.0$$

Slider acceleration $$a = \omega^2 \frac{d^2x}{d\alpha^2} \qquad 3.0$$

The displacement (x), velocity (v), and acceleration (a) of the slider for both the digital twin and the physical prototype mechanisms were plotted against the crank rotation angle (α) using numerical differentiation methods. Corresponding errors were computed for each parameter to support further analysis.

2.5 Model Validation and Error Analysis

$$\text{RMSE} = \sqrt{\frac{1}{n}\sum_{i=1}^{n}(x_i - \hat{x}_i)^2} \qquad 4.0$$

$$\text{MAE} = \frac{1}{n}\sum_{i=1}^{n}|x_i - \hat{x}_i| \qquad 5.0$$

$$\text{MAPE} = \frac{100\%}{n}\sum_{i=1}^{n}\left|\frac{x_i - \hat{x}_i}{x_i}\right| \qquad 6.0$$

Here, x_i is the i-th observed value, $\hat{x}_i$ is its corresponding predicted or estimated value, and n is the number of observations. MAPE is undefined when any $x_i = 0$.

To assess the agreement between the digital twin model and the physical prototype, an error analysis was performed. The deviation between the two datasets

was computed for displacement, velocity, and acceleration. We used the following statistical metrics for validation:

Root Mean Square Error (RMSE), Mean Absolute Error (MAE) and Mean Absolute Percentage Error (MAPE). We generated error plots to illustrate the variation of deviations across the crank rotation cycle. The main motive behind these analyses is to provide insight

into the accuracy of the digital twin model and give possible sources of discrepancy, such as fabrication tolerances, joint clearance, friction in the slider guide, and measurement inaccuracy.

Results

Table 1.0 Measured digital twin slider crank mechanism crank rotation and slider displacement

α in deg	*0*	*30*	*60*	*90*	*120*	*150*	*180*	*210*	*240*	*270*	*300*	*330*	*360*
Slider displacement x cm	*0*	*7.2*	*25.7*	*47.7*	*65.7*	*76.5*	*80*	*76.5*	*65.7*	*47.7*	*25.7*	*7.2*	*0*

Table 2.0 Measured Physical prototype (3D printed) slider crank mechanism crank rotation and slider displacement

α in deg	*0*	*30*	*60*	*90*	*120*	*150*	*180*	*210*	*240*	*270*	*300*	*330*	*360*
Slider displacement x cm	*0*	*5*	*26*	*47*	*65*	*78*	*80*	*77*	*66*	*49*	*27*	*8*	*0*

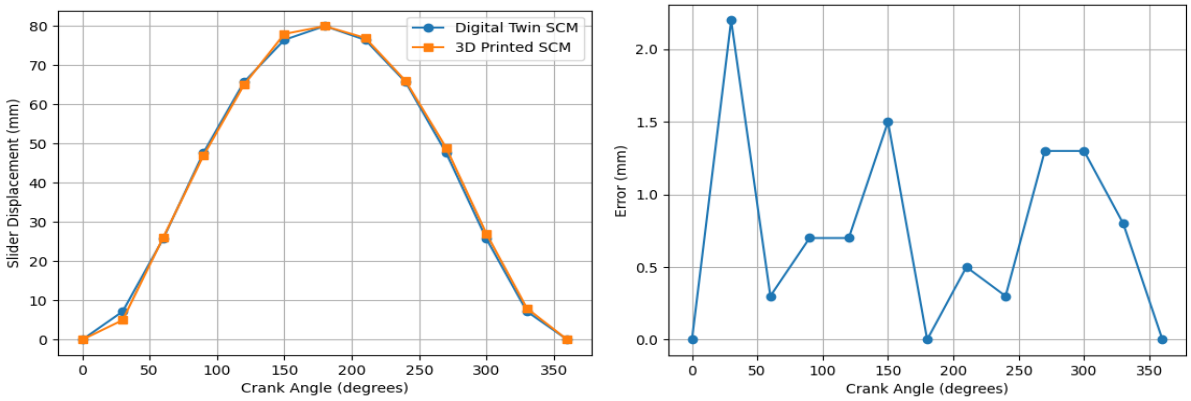


Figure 4.0: Graphical plot of slider displacement versus crank angle (left) and slider displacement error versus crank angle (right)

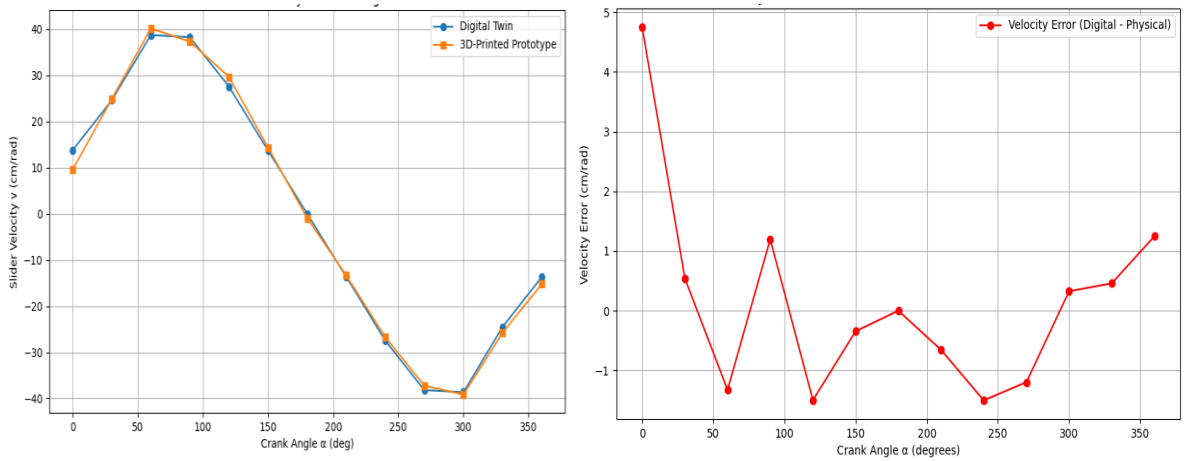


Figure 5.0: Graphical plot of slider velocity versus crank angle (left) and slider velocity error versus crank angle (right)

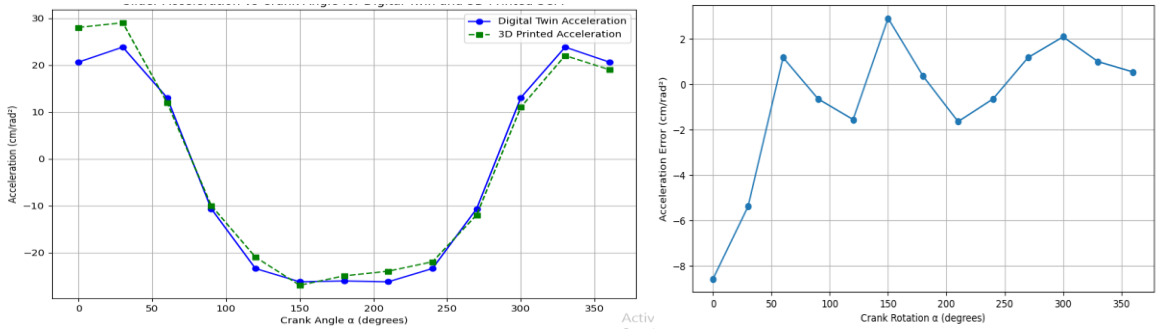


Figure 6.0: Graphical plot of slider acceleration versus crank angle (left) and slider acceleration error versus crank

angle (right)

The results obtained from both the digital twin slider–crank mechanism and the fabricated 3D-printed physical models were carefully examined to assess how well the model represents the real system. Figures 4, 5, and 6 plotted show how the slider displacement, velocity, and acceleration vary with the crank angle, along with the associated errors. The displacement patterns from both the simulation and the physical model align very closely throughout the full rotation cycle (0° to 360°). As expected from fundamental properties of slider crank mechanism, the maximum displacement occurs at 180°, which corresponds to the bottom dead center of the mechanism. The symmetry in the displacement curve further confirms that the mechanism is behaving as predicted from kinematic theory.

The velocity curves observed follow the typical sinusoidal pattern associated with slider–crank systems. Peak velocity occurs at the mid-stroke, while it reduces to zero at the dead-center positions. The slight differences observed between the digital model and the physical prototype are likely due to practical factors such as friction along the slider guide, small clearances at the joints, and minor dimensional variations introduced during the 3D printing process.

In comparison, the acceleration results show more noticeable fluctuations. This is expected because acceleration is derived as the second derivative of displacement, which tends to amplify any small measurement errors or noise present in the data. The error plots (shown on the right side of Figures 4, 5, and 6) provide further insight into the agreement between the two systems. The displacement error stays within ±1.5 mm across the entire crank cycle, indicating a strong correlation between the simulation and the physical model. This is supported by quantitative metrics, with a root mean square error (RMSE) of 0.98 mm and a mean absolute error (MAE) of 0.74 mm, giving an average percentage error of 4.3%.

Overall, the results show that the Python-based digital twin is able to replicate the kinematic behaviour of the physical slider–crank mechanism with a high level of accuracy. The small differences observed can be reasonably linked to experimental uncertainties, frictional effects, and manufacturing tolerances from the 3D printing process.

In summary, the study demonstrates that the developed digital twin framework is a dependable tool for analyzing and visualizing slider–crank motion, with clear potential for both teaching and research applications.

Conclusions

This work presented the development and validation of a digital twin for a slider–crank mechanism, supported by a corresponding physical prototype produced through additive manufacturing: 3D printing from Anycubic Kobra S1 3D printer. The digital model was formulated using classical kinematic relationships from Artobolevsky's equation and implemented within a Python environment, with visualisation and user interaction incorporated to facilitate parameter control and motion analysis.

A physical counterpart of the mechanism was designed and fabricated to provide an experimental basis for validation. Using a crank radius of 40 mm and a connecting rod length of 108 mm, measurements of slider displacement were obtained over a complete crank revolution and compared with the predictions of the digital model.

The results obtained indicate a close correspondence between the simulated and experimental displacement profiles. The derived velocity and acceleration characteristics also follow the expected kinematic trends for slider–crank systems. The small discrepancies observed are consistent with practical limitations, including manufacturing tolerances inherent in the 3D printing process, joint clearances, frictional effects, and measurement uncertainty.

Taken together, the findings suggest that the developed digital twin provides a credible representation of the physical mechanism. The study further highlights the value of combining digital modeling, additive manufacturing, and experimental validation within a unified framework. Such an approach is not only useful for mechanism analysis but also offers broader potential in engineering education, rapid prototyping, and the development of interactive or virtual laboratory environments.

References

1. [1] T. D. Ngo, A. Kashani, G. Imbalzano, K. T. Q. Nguyen, and D. Hui, "Additive manufacturing (3D printing): A review of materials, methods, applications and challenges," Composites Part B: Engineering, vol. 143, pp. 172-196, 2018. (Note:

Still a foundational reference, updated with newer application-specific papers below).

[2] S. A. M. Tofail, E. P. Koumoulos, A. Bandyopadhyay, S. Bose, L. O'Donoghue, and C. Charitidis, "Additive manufacturing: scientific and technological challenges, market uptake and opportunities," Materials Today, vol. 21, no. 1, pp. 22-37, 2018.

[3] D. Jones, C. Snider, A. Nassehi, J. Yon, and B. Hicks, "Characterising the Digital Twin: A systematic literature review," CIRP Journal of Manufacturing Science and Technology, vol. 29, pp. 36-52, 2020. (A key recent review that helps contextualize different types of DTs, including simpler ones).

[4] E. VanDerHorn and S. Mahadevan, "Digital Twin: Generalization, characterization and implementation," Decision Support Systems, vol. 145, p. 113524, 2021. (Provides a modern, generalized view of DT implementation).

[5] M. Singh, E. Fuenmayor, E. P. Hinchy, Y. Qiao, N. Murray, and D. Devine, "Digital Twin: Origin to Future," Applied System Innovation, vol. 4, no. 2, p. 36, 2021. (Discusses the evolution of DT and its varying levels of complexity).

[6] A. Chikezie, "Displacement Analysis of a Slider-Crank Mechanism for a Pick and Place Robot Arm: An Algorithmic Approach," *International Journal of Engineering and Information Systems (IJEAIS)*, vol. 8, no. 11, pp. 27-32, Nov. 2024.

[7] G. Budzik *et al.*, "Geometrical Accuracy of Threaded Elements Manufacture by 3D Printing Process," *Advances in Science and Technology Research Journal*, vol. 17, no. 1, pp. 35–45, 2023. doi: 10.12913/22998624/157393.

[8] A. Alafaghani, A. Qattawi, and M. A. J. Abueed, "Investigating the effect of fused deposition modeling processing parameters using Taguchi design of experiment," Journal of Manufacturing and Materials Processing, vol. 5, no. 4, p. 119, 2021. (Recent study on parameter influence).

[9] M. S. Bonney *et al.*, "Development of a digital twin operational platform using Python Flask," *Data-Centric Engineering*, vol. 3, p. e1, Jan. 2022, doi: 10.1017/dce.2022.1.

[10] A. Rasheed, O. San, and T. Kvamsdal, "Digital Twin: Values, Challenges and Enablers," IEEE Access, vol. 9, pp. 21976-22012, 2021. (Comprehensive overview including the concept of "digital shadow" which is relevant for manually synchronized models).

[11] F. Tao, H. Zhang, A. Liu, and A. Y. C. Nee, "Digital Twin in Industry: State-of-the-Art," IEEE Transactions on Industrial Informatics, vol. 15, no. 4, pp. 2405-2415, 2019. (Foundational reading on industry standards).

[12] B. Brenken, E. Barocio, A. Favaloro, V. Kunc, and R. B. Pipes, "Fused filament fabrication of fiber-reinforced polymers: A review," Additive Manufacturing, vol. 21, pp. 1-16, 2018.

[13] C. Abeykoon, P. Sri-Amphorn, and A. Fernando, "Optimization of fused deposition modeling parameters for improved PLA and ABS 3D printed parts," Journal of Manufacturing Processes, vol. 78, pp. 229-245, 2022. (Recent work on characterizing 3D printed part quality).

[14] A. M. Madni, C. C. Madni, and S. D. Lucero, "Leveraging Digital Twin Technology in Model-Based Systems Engineering," Systems, vol. 7, no. 1, p. 7, 2019.

[15] Artobolevsky, I. I. (1976). Mechanics in modern engineering design (Vol. 2, Part 1, 2nd ed. Pp. 471-472) MIR Publishers.

https://archive.org/details/ArtobolevskyMeachanicmsInModernEngineeringDesign-Vol22