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DIGITAL TWIN – NEW TREND IN AIRCRAFT MAINTENANCE

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Abstract

Safety has always been the main concern of successful aircraft operation. Key part of the operation has to be maintenance, which not only removes defects should they arise, but also prevents them from happening in the first place. For this very reason it is necessary to have a reliable maintenance program and practices. In recent years emphasis has been posed on thorough analysis of aircraft and its systems. This is made ever so easier thanks to tools such as the digital twin. Our goal is to research this recent trend and showcase its possibilities. This wouldn't be possible without our previous underlying studies about Industry 4.0, its related matters including maintenance, as well as digital twin itself. Finally, it is important to note that the main goal of our work is not necessarily the creation of the twin, but rather the subsequent measurements, tests and analysis.

Keywords

keyword 1, keyword 2, keyword 3

1. INTRODUCTION

Maintenance is a key component of a successful aircraft operation. Rapid advancements of not only aircraft, but also their systems, instruments and engines require adequate maintenance program. In such programs, there is an ever-increasing need for modern technology and advanced procedures. Should companies take steps towards optimised maintenance, including recent solutions with complex systems, there will be an abundance of data. Our researched topic, digital twin, integrates well with these operations. Its use is becoming common, especially in commercial aviation. Different applications exist, where our aim is to explore the potential of digital twins in general aviation, more specifically in maintenance therein.

2. BACKGROUND

Each period in history is marked with certain characteristics of its industry. Industrial revolutions brought extensive advancements which completely changed set practices. Optimised workflow connected with new technologies meant lower overall costs for even better results. However, progress never halted, on the contrary it only pushed even further. It had never taken long before the next breakthrough has taken the market by storm. Not only from economic standpoint, was it necessary to swiftly adjust to keep up with the competition. Furthermore, new trends improved the speed, effectiveness, ecology and quality of products and operations [1].

First industrial revolution dates to the end of the 18th century when steam machines improved productivity. They reduced the need for manual labour of people and animals. Trains also helped with the distribution of materials and products. Nevertheless, machinery took its toll on the environment with severe pollution. In return, their work was also not reliable which perhaps foresaw further advancements in the future [2].

From 1870 we may talk about the second industrial revolution which continued the boom of first revolution with its own additions. Forth came inventions such as the first plane of the Wright brothers. Cities took the opportunities of electricity while production plants made use of production lines. Even the beginnings of connectivity in large cities could be seen in the form of telephone lines [3].

After the casualties of first and second world war researchers got inspired by revolutionary equipment used in said wars and here came the third revolution. Characteristic to this era which concerns us even today is the transfer from analogue and mechanical to digital technologies and data. Industry 4.0 further enhances these technologies and puts emphasis on maximum usage of internet and virtual space in general [3].

That brings us to one of the highlights of our current era in fact, which is IoT (Internet of Things). It enables seamless connection between physical objects and computer systems. Thanks to the integration of electronics, software and sensors, it is even possible to control devices remotely [4].

3. DIGITAL TWIN

With all the advancements, the idea of mirroring a physical object has become very attractive. By creating a virtual copy of a real product, we can make all the operations from design through manufacture to maintenance much easier and more precise. This concept has already seen various definitions and interpretations, but the general idea always stays the same:

- Exchange data between both versions and further analyse them.
- Ensure interchangeable work on either version by keeping both identical.
- Maintain and update each version [6].

While the concept of a digital twin stems back all the way to the end of 20th century, it was not until 2003 that dedicated research started outside specialized organizations like NASA. That year M. Grieves proposed his paper on a digital twin as we know it today. The proposal stood on three bases which are the physical product, its virtual copy and their connection. In 2005 he also came up with three categories of digital twin:

- DTP (digital twin prototype) – created before the physical product,
- DTI (digital twin instance) – with the intention of testing and
- DTA (digital twin aggregate) – which gathers data and diagnosis [7].

The breakthrough of this technology worldwide came from 2012 through 2014, when said technology was applied in various sectors around the world. In 2017, digital twin was said to be one of the best technological trends [8].

3.1. Principle

The basis of digital twin is the collection of data fed from sensors on the physical object. These data allow the system to analyse and compute the past, present and future states of the product. That comes with higher safety in the form of anticipation of errors and relevant troubleshooting, and overall, a smoother operation. From the point of view of manufacturing, digital twin presents an assurance of the success of the actual product. On the other hand, in maintenance it ensures optimal and most importantly safe operation. There is even an aspect of comfort, where a mechanic for instance does not have to work in proximity of physical object at all times. The possibilities are without a doubt limitless but certain requirements stay in place no matter what [9].

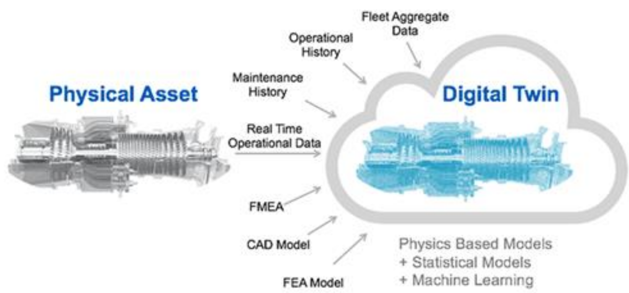

Figure 1 - Relationship between physical asset and digital twin [4]

Each of the twins exist within their own space (virtual and physical). It is far more beneficial during the development of a new product to create the digital twin first. That goes for updates further down the line as well. In the digital space mistakes and faults do not pose as much of a threat as in the real world. Therefore, this space serves as an excellent testing ground. Furthermore, it contributes with various useful built-in functions depending on the specific software used. It must not be forgotten however, that the ultimate focus should be placed on the physical object, because without it, the whole concept remains a fantasy so to speak. Digital twin integrates itself by also communicating with both the object and people involved in the operation. It is of utmost importance therefore, that the concerned personnel understand the innerworkings of the entire system. This may be achieved by the digital twin sharing its data including the applied processes. In this manner, humans can interfere in time should the system malfunction. By storing and analysing actions leading to an error, it is also possible to prevent similar accidents in the future. This can be further automatized by assigning such preventive action to the system itself [10].

3.2. Preparation

Before even pursuing just the creation of digital twin it is often necessary to carry out tests and simulations. One of these is FMEA (Failure Mode and Effect Analysis) which can uncover underlying threats and imperfections before even starting the project itself. Upon discovery, threats can identified and their consequences specified. Controlling and decision-making of hazards is a science of its own. FMEA has been already used during APOLLO program in order to optimise and verify the project. The method is made of two phases:

- Identification – where we identify:
  - potential errors,
  - their consequences and
  - their root.
- Numerical phase – where we calculate the extent of risks [11].

Another key element of the preparation for a project is FEA (Finite Element Analysis), where the effect of outside forces on tested subject are found. Most products are expected to function in various conditions which can sometimes be extreme. During the analysis, object is meshed with finite elements as the name implies and subsequent calculations are made feasible. With more powerful hardware comes the opportunity to create more detailed mesh leading to more precise results. However, computing time can still be extended [12].

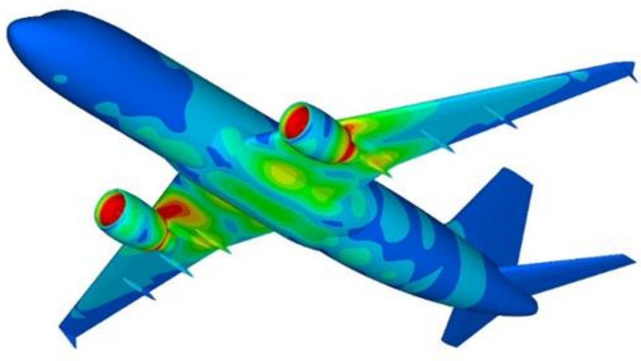

Figure 2 - FEA [13]

Overall, the general goal during preparation phase is to gain awareness. Heap of data presents little to no benefit to a human being unless it is further processed. In order to make data easier to digest for the human mind, we can transform it, simplify it and present it in a more appealing way. Such ways include but are not limited to:

- Visualisation – which makes the task more transparent.
- Simulation models – which serve as the core of most research.
- Signal processing – graphical interpretation
- Deep learning – which is the most complex way by means of artificial intelligence [14].

These days we have the option to walk the extra mile by using AR (Augmented Reality) and similar technology to further optimise our work. The ability to work in both virtual and physical environment at the same time has never been easier. All previously mentioned factors, especially awareness, pose perfect candidates for utilization of combined workspace. In such space outputs are not limited to numerical and linguistic data but rather present prime opportunity for visualisation in real time. In complex operations with multiple large components it might prove very beneficial to connect multiple digital twins, where output data are exchanged and compared for maximum synergy [10].

With the open interconnected operation that digital twins present, come certain liabilities. There are cybernetic threats which pose multitude of threats on their own. However, even within the specific organisation lie threats. It is not uncommon for companies to incline towards cheaper materials for the sake of lower costs. Such materials endanger every phase of operations and they should be avoided. Digital twin infrastructure protects against inferior components by means of RFID (Radio Frequency Identification). This technology is similar to bar codes and they assure that every part used is of adequate quality [10].

Although digital twins are appreciated for their benefits, they are not guaranteed for every stakeholder. Not all products and services are complex enough to justify the large investment and upkeep. Its costs come mainly in the form of required hardware, software and their maintenance. In general, projects that can greatly benefit from digital twins are:

- Physically large projects,
- Mechanically complex projects,
- Heavy machinery and
- Production [15].

Digital twin market saw a severe decline during COVID-19. Logistics suffered the most and the other areas followed. Albeit the motivation for application of the technology in medicine, the delays posed too big of a hit for the entire market. Before the pandemic there was an ever-increasing demand for smart technology in cities but with the arrival of COVID-19 these projects got postponed [16].

4. AIRCRAFT MAINTENANCE

In order to operate aircraft safely, it is vitally important to maintain them in not only functional state but rather durable. Every component of an aircraft is vital to safe flight and it is therefore necessary to have a proper maintenance program in place. With the development of more and more advanced aircraft come the need for cutting-edge maintenance as well. Basic maintenance procedures are not sufficient anymore and companies have to apply modern methods [17].

Looking back at the development of maintenance throughout history, the first generation provided bare minimum to keep aircraft in the air. Faults were repaired after they had already materialised. With the arrival of jet aircraft came a need for adequate maintenance. Airlines had hundreds of lives in their hands and any incident meant immoderate financial losses. Authorities also started applying regulations which have been getting stricter by the year to ensure safety of all lives onboard. Extensive maintenance at the time meant performing inspections, replacements and repairs at fixed times. This methodology went by the name "Hard-Time maintenance" and while its practices are to some extent used until now, on its own it presents very inefficient operation. Direct upgrade to Hard-Time maintenance is "On-Condition", which is defined by the FAA (Federal Aviation Administration) as:

"a preventive primary maintenance process that requires a system, component, or appliance be inspected periodically or checked against some appropriate physical standard to determine if it can continue in service. The standard ensures that the unit is removed from service before failure during normal operation. These standards may be adjusted based on operating experience or tests, as appropriate, IAW a carrier's approved reliability program or maintenance manual." [18]

Upon the arrival of large airliners involved parties discovered that even the most recent methods are insufficient and there is an immediate need of further advancements in maintenance. Old ways were impractical and costly for such complex machines and they posed unacceptable time contribution. Various interested parties including Boeing formed MSG (Maintenance Steering Group) which placed focus on reliability with RCM (Reliability Centered Maintenance) [17].

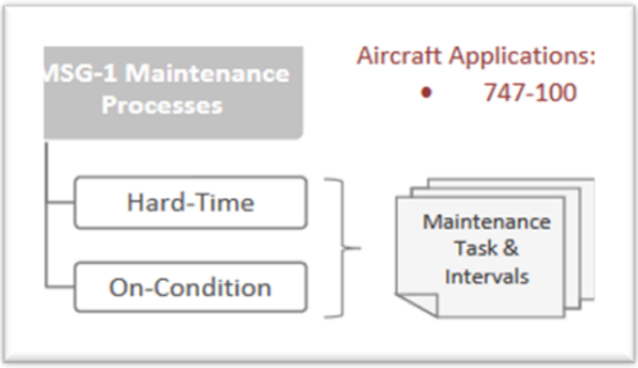

Figure 3 - MSG-1 [19]

4.1. Digital twin in maintenance

The digital twin concept was used in 2011 by researcher E. J. Tuegel and his team for forecasting and life management in the framework of predicting aircraft structural life [20]. Later, B. R. Seshadri and T. Krishnamurthy used it for damage detection, classification and isolation [21].

Effective damage detection is key, but despite developments in computing and mathematical optimization, the human component remains essential. Autonomous maintenance systems need to evaluate different situations with the help of a digital twin. For a digital twin, the following aspects must be taken into account:

- Structural – contains information about the structure, including the interrelationships and functioning of the components
- Product - it is a representation of components
- Performance - collects data generated by the system in real time [22]

These aspects highlight why technology data is needed at every stage of the system's life cycle. The ability to generate and store information is essential for the proper operation of autonomous maintenance. Information must be stored in a standard format and delivered to the relevant interfaces. The digital twin integrates sensor data from onboard systems, maintenance history, and other historical records [23].

One of the research questions in recent years on the topic of digital twin and maintenance automation is: "If the simulation and the physical environment are shaped in the same way, will this allow the self-learning algorithm to guide itself without manual intervention?" This would solve the previously mentioned problems and reduce the necessary human factor. It is a promising solution as previous parameters would not be needed to fine-tune the system. The system could be adapted to more complex situations using the information collected so far [22].

As already mentioned, we know several types of maintenance, each type applying a different strategy to achieve the same goal - a functional product. In the aviation sector (and others), maintenance represents a significant cost that justifies the investment in a digital twin. The main idea would therefore be the optimization of maintenance processes in order to reduce costs [24].

By predicting the condition of the product, the digital twin can adjust the maintenance schedule accordingly, which is all the more important in the harsh conditions in which the product (in our case, the aircraft) operates. In these activities, there is still not enough emphasis and the possibilities of the virtual environment are not appreciated. For optimal results, it is necessary to connect the virtual and physical environment. However, there are basic requirements without which the process cannot function properly:

- The digital twin must describe the physical object in detail.
- The connection between the virtual and the physical world must take place naturally and without problems.
- Individual information must be combined and appropriately processed [24].

4.2. 5D Digital twin

While initially all digital twin research focused on three-dimensional architecture, Tao et al. were devoted to 5D. In the case of 3D, the twin is built on the basis of a physical object, a virtual model and their connection. The remaining two dimensions in the 5D structure are data and functions. In this structure proposed by Tao, we can obtain more comprehensive and accurate information by combining the output data from the virtual and physical versions [24].

The proposal also accurately describes the principle of the new architecture, in which a 5D digital twin is used to create PHM (Prognostics and Health Management). Within this structure, we distinguish two types of faults. These are gradual disturbances that we can predict and intervene in and sudden disturbances that occur unexpectedly. The principle is shown schematically in fig. 4. The scheme is divided into three parts, namely: observation, analysis and decision-making [24].

In the first part, observation, 3 primary steps are covered. First of all, it is necessary to model and calibrate the digital twin. Tao refers to a physical object and a virtual copy with the abbreviations PE (Physical Entity) and VE (Virtual Equipment) respectively. In case these two objects differ, it defines the following solutions: either we manually calibrate the VE using the simplest method or we maintain CN_PV (Connection model_Physical Entity-Virtual Equipment) to ensure constant communication between PE and VE. In this step, we can also notice other relevant factors that also have their own abbreviations. Ss (Services model) includes services for both PE and VE. It optimizes PE operation and ensures VE accuracy by continuously calibrating VE parameters based on PE activity. DD (Data model) is a subset of data from individual sources, namely: Dp – data from PE; Dv – data from VE; Ds – data from Ss and other data [24].

In the second step, we focus on simulations and interaction of objects. Tao describes this and other steps mathematically using a number of parameters. Simply put, in step 2 we address the work and state of the PE. This step is directly related to other steps that build on it. Step 3 just compares the work and status of the PE with the VE and makes sure the values are the same/similar with tolerances. If the results are correct and consistent, we move smoothly to step 4, where we detect the wear of the device. Otherwise, when the results do not meet expectations, we skip to step 5, where we look for the cause of the discrepancy, which is caused by either PE or VE, where PE is the more dangerous case, and we continue to step 6. In the sixth step, we identify and predict the cause of the malfunction, which can be:

- gradual or
- sudden [24].

If step 5 detects irregularities in the VE, it goes back to step 1 and the whole process is reset. If we get to the last step, it defines the strategy of the maintenance itself. The maintenance is adapted to the detected results and is tested first on the VE [24].

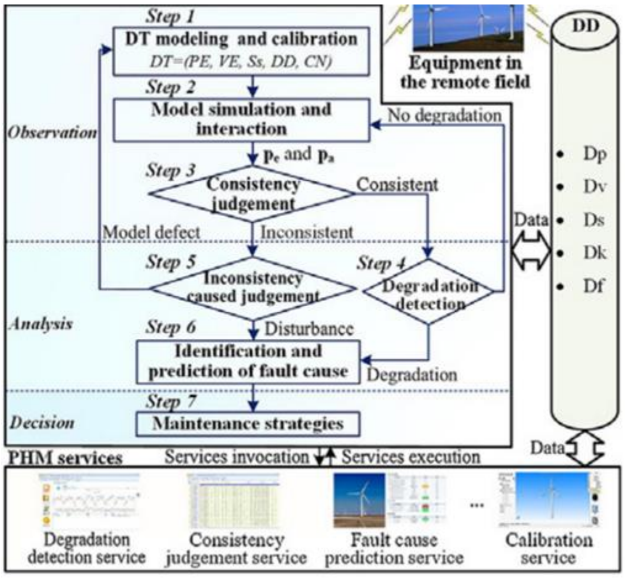

Figure 4 - PHM structure with 5D digital twin [24]

5. WORK RESULTS

With the help of software such as Autodesk Inventor and Unity, we were able to create a prototype of our own. Our digital twin is based on Lycoming AEIO-360-A1B6 aircraft engine used amongst others in Zlín 242. Our proposal incorporates a functional 3D model of said engine and a custom program which displays necessary maintenance steps for the requested engine part.

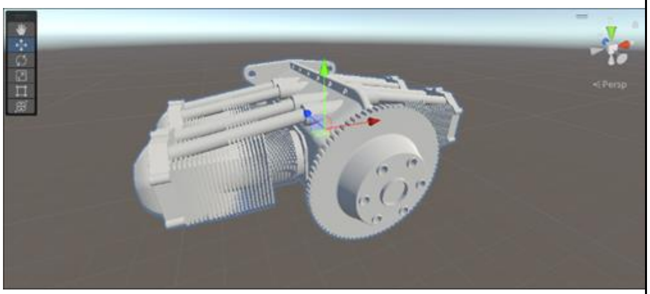

Figure 5 - 3D model

First, we modeled all of the required parts individually based on maintenance documentation, real life observations, measurements and calculations. Making the parts separately made it not only easier to adjust them and keep track of them, but also later proved useful in their detection for the purposes of our virtual checklist program.

We were able to assemble the parts into the final object including their adequate movements, clearances and synchronization. By exporting the object from Inventor to Unity, we could further work with it as a part of the virtual checklist. We set the desired camera angle and distance, keeping in mind pleasant and simple user experience and started coding.

We coded the program in C#, creating 3 separate scripts. First script controls the camera when the program is running based on the user input. This allows not only the inspection of the model, but also makes it possible to select parts which may not be in view, thus not selectable.

```
// Handle camera rotation
if (Input.GetMouseButtonDown(1))
{
    previousPosition = cam.ScreenToViewportPoint(Input.mousePosition);
}
else if (Input.GetMouseButton(1) && !isZooming)
{
    // Rotate the camera around the target
    Vector3 newPosition = cam.ScreenToViewportPoint(Input.mousePosition);
    Vector3 direction = previousPosition - newPosition;

    float rotationAroundYAxis = -direction.x * 180;
    float rotationAroundXAxis = direction.y * 180;

    cam.transform.position = target.position;

    cam.transform.Rotate(new Vector3(1, 0, 0), rotationAroundXAxis);
    cam.transform.Rotate(new Vector3(0, 1, 0), rotationAroundYAxis, Space.World);

    // Move the camera back to the target
    cam.transform.Translate(new Vector3(0, 0, -distanceToTarget));

    // Finally, update the previous position
    previousPosition = newPosition;
}
```

Figure 6 - Camera control script showcase

Next, we created the maintenance instructions script, which creates a pop-up window on user interface, displaying necessary maintenance procedures on selected component. This is the core of the whole program, and all the other parts involve around it. We decided to split the window into a header and main text which show the name of maintenance step and instructions correspondingly. These elements are also editable outside of IDE (Integrated Development Environment) making the program even more user-friendly and adjustable to ones liking.

```
using System.Collections;
using System.Collections.Generic;
using UnityEngine;
using UnityEngine.UI;
using TMPro;

public class InstructionsPanel : MonoBehaviour
{
    // Singleton instance so that other scripts can access the instructions panel
    public static InstructionsPanel instance;

    private void Awake()
    {
        if (instance == null)
        {
            instance = this;
        }
        else
        {
            Destroy(gameObject);
        }

        // Hide the instructions panel by default
        gameObject.SetActive(false);
    }
```

Figure 7 - Maintenance instructions script showcase

Lastly, it was necessary to develop a way for the user to view instructions of the desired part but also open the maintenance instructions window in the first place. For the sake of simplicity, track-keeping and troubleshooting we decided to implement this in a separate script too. Since right mouse click controls camera, we assigned left click to opening of the window.

```
using UnityEngine;
using UnityEngine.UI;

public class ClickForInstructions : MonoBehaviour
{
    // Name of the part that the instructions are for
    public string partName = "Placeholder Part";
    [TextArea(50, 10)]
    // Instructions to display in the UI object
    public string instructionsText = "Placeholder instruction text";

    void OnMouseDown()
    {
        // Show instructions panel and update instructions text
        // Access the instance of the instructions panel
        InstructionsPanel instructionsPanel = InstructionsPanel.instance;
        instructionsPanel.gameObject.SetActive(true);
        // Call the ChangeText method on the instructions panel
        instructionsPanel.GetComponent<InstructionsPanel>().ChangeText(instructionsText, partName);
    }
}
```

Figure 8 - Maintenance window initiation script showcase

6. CONCLUSION

One of the beneficial technologies in aircraft maintenance is the digital twin. A virtual copy of a physical object carries countless advantages, and additional functions and uses are constantly being developed. We transform the necessary information from a paper form, in which it is confusing and needs to be constantly manually updated, to a digital form, in which new possibilities open up. Data can be automatically updated and forwarded via the Internet. Their representation is much clearer and the system will produce other adequate outputs.

In our work, we investigated the use of a digital twin in general aviation, in the form of a virtual checklist. From the operator's point of view, it may seem like modern technologies and digitization are not economically advantageous, as they present a significant investment. However, our proposal represents a simpler concept that would not represent such significant costs in terms of maintenance and overall operation.

The first phase of our project was the creation of a Lycoming engine model. The modeled engine was used to create a virtual checklist, which we developed in the Unity software environment. We programmed it in the C# programming language.

One of the shortcomings of our program that we encountered is the problem of getting to the internal components. Parts that are inside the crankcase, cylinders, etc. are not possible for users to select and display their relevant maintenance procedures. We propose to solve the problem by splitting the object by means of a standalone function into individual components that the user can see and choose. An alternative solution may be to list the components in a separate window when selecting the unit.

The concept can be used even more effectively for the aircraft as a whole, not just for the engine. In such a case, all the obtained information would have a greater value, as it can be compared and merged with the values of other sub-assemblies and parts. Such a project presents a number of additional challenges and is clearly beyond the scope of our work.

REFERENCES

[1] B. Bukova, E. Brumercikova, L. Cerna, and P. Drozdziel, “The Position of Industry 4.0 in the Worldwide Logistics Chains,” LOGI - Sci. J. Transp. Logist., vol. 9, no. 1, pp. 18–23, May 2018, doi: 10.2478/logi-2018-0003.

[2] R. Karaba, “Analýza súčasného stavu Logistiky 4.0 v slovenskom priemysle a návrh všeobecnej metodiky pre jej rozvoj a implementáciu,” Diplomová práca, Slovenská technická univerzita v Bratislave, Trnava, 2018.

[3] T. Patro, “Priemysel 4.0,” Buď FIT, Feb. 14, 2018. https://casopis.fit.cvut.cz/tema/priemysel-4-0/ (accessed Feb. 24, 2023).

[4] L. Sotoňák, “Trendy v údržbe a technickom servise,” Bakalárska práca, Žilinská univerzita v Žiline, Žilina, 2020.

[5] B. Balga, “SMART factory - inteligentní továrna,” IPA Slovakia. https://www.ipaslovakia.sk/clanok/smart-factory-inteligentni-tovarna (accessed Feb. 24, 2023).

[6] S. Boschert and R. Rosen, “Digital Twin—The Simulation Aspect,” in Mechatronic Futures, P. Hehenberger and D. Bradley, Eds., Cham: Springer International Publishing, 2016, pp. 59–74. doi: 10.1007/978-3-319-32156-1_5.

[7] M. W. Grieves, “Product lifecycle management: the new paradigm for enterprises,” Int. J. Prod. Dev., vol. 2, no. 1/2, p. 71, 2005, doi: 10.1504/IJPD.2005.006669.

[8] “Gartners Top 10 Technology Trends 2017.” https://www.gartner.com/smarterwithgartner/gartners-top-10-technology-trends-2017 (accessed Feb. 24, 2023).

[9] M. Lohtander, N. Ahonen, M. Lanz, J. Ratava, and J. Kaakkunen, “Micro Manufacturing Unit and the Corresponding 3D-Model for the Digital Twin,” Procedia Manuf., vol. 25, pp. 55–61, 2018, doi: 10.1016/j.promfg.2018.06.057.

[10] [10] M. W. Grieves, “Virtually Intelligent Product Systems: Digital and Physical Twins,” in Complex Systems Engineering: Theory and Practice, S. Flumerfelt, K. G. Schwartz, D. Mavris, and S. Briceno, Eds., Reston, VA: American Institute of Aeronautics and Astronautics, Inc., 2019, pp. 175–200. doi: 10.2514/5.9781624105654.0175.0200.

[11] M. Tichý, Ovládání rizika: analýza a management. Nakladatelství C H Beck, 2006.

[12] [12] B. Zhuming, Finite Element Analysis Applications. Elsevier, 2018. doi: 10.1016/C2016-0-00054-2.

[13] “Finite Element Analysis in a Nut Shell.” https://www.stressebook.com/finite-element-analysis-in-a-nut-shell/ (accessed Feb. 25, 2023).

[14] W. Kuehn, “Simulation in Digital Enterprises,” in Proceedings of the 11th International Conference on Computer Modeling and Simulation, North Rockhampton QLD Australia: ACM, Jan. 2019, pp. 55–59. doi: 10.1145/3307363.3307370.

[15] “What is a digital twin? | IBM.” https://www.ibm.com/topics/what-is-a-digital-twin (accessed Mar. 06, 2023).

[16] “Digital Twin Market Size & Forecast [Latest],” MarketsandMarkets. https://www.marketsandmarkets.com/Market-

Reports/digital-twin-market-225269522.html (accessed Mar. 06, 2023).

[17] M. Janovec, “Technická údržba lietadiel,” Žilinská univerzita v Žiline, 2022.

[18] “Soft Time, Hard Time, and OC CM Components.” http://www.faa-aircraft-certification.com/soft-time-hard-time-and-oc-cm-components.html (accessed Feb. 25, 2023).

[19] S. P. Ackert, “Basics_of_Aircraft_Maintenance_Programs_for_Financiers,” 2010.

[20] E. J. Tuegel, A. R. Ingraffea, T. G. Eason, and S. M. Spottswood, “Reengineering Aircraft Structural Life Prediction Using a Digital Twin,” Int. J. Aerosp. Eng., vol. 2011, pp. 1–14, 2011, doi: 10.1155/2011/154798.

[21] B. R. Seshadri and T. Krishnamurthy, “Structural Health Management of Damaged Aircraft Structures Using Digital Twin Concept,” in 25th AIAA/AHS Adaptive Structures Conference, Grapevine, Texas: American Institute of Aeronautics and Astronautics, Jan. 2017. doi: 10.2514/6.2017-1675.

[22] S. Khan, M. Farnsworth, R. McWilliam, and J. Erkoyuncu, “On the requirements of digital twin-driven autonomous maintenance,” Annu. Rev. Control, vol. 50, pp. 13–28, 2020, doi: 10.1016/j.arcontrol.2020.08.003.

[23] S. Khan and T. Yairi, “A review on the application of deep learning in system health management,” Mech. Syst. Signal Process., vol. 107, pp. 241–265, Jul. 2018, doi: 10.1016/j.ymssp.2017.11.024.

[24] F. Tao, M. Zhang, Y. Liu, and A. Y. C. Nee, “Digital twin driven prognostics and health management for complex equipment,” CIRP Ann., vol. 67, no. 1, pp. 169–172, Jan. 2018, doi: 10.1016/j.cirp.2018.04.055.