engineering proceedings

MDPI

Proceeding Paper

A Preliminary Study on Computer Aided Process Planning for Generating Additive Manufacturing Products via 3D/4D/5D Printing †

Izzah Nadhilah Ilias and Mohd Salman Abu Mansor *

School of Mechanical Engineering, Engineering Campus, Universiti Sains Malaysia, Seri Ampangan, Seberang Perai Selatan, Nibong Tebal 14300, Pulau Pinang, Malaysia

* Correspondence: mesalman@usm.my

† Presented at the 8th Mechanical Engineering, Science and Technology International Conference, Padang Besar, Perlis, Malaysia, 11–12 December 2024.

Abstract: This paper presents an integrated CAD/CAM system that can be used for Computer Aided Process Planning to interact or automate 3D/4D/5D printing process towards Industry 5.0. By creating a new algorithm, macro is developed that has the capability to determine any suitable type of printing process whether 3D, 4D or 5D printing for generating Additive Manufacturing products. The methodology of this study is focused starting from designing 3D CAD models for Additive Manufacturing products until generating 3D/4D/5D printing process planning by a creation of macro. The algorithm is tested by printing simulations from 3D printing extended up to 5D printing.

Keywords: process planning; additive manufacturing; 3D/4D/5D printing; CAD/CAM; Industry 5.0

check for updates

Academic Editors: Noor Hanita Abdul Majid, Agus Dwi Anggono, Waluyo Adi Siswanto, Tri Widodo Besar Riyadi, Mohammad Sukri Mustapa, Nur Rahmawati Syamsiyah and Afif Faishal

Published: 7 February 2025

Citation: Ilias, I.N.; Abu Mansor, M.S. A Preliminary Study on Computer Aided Process Planning for Generating Additive Manufacturing Products via 3D/4D/5D Printing. *Eng. Proc.* **2025**, *84*, 44. https://doi.org/10.3390/engproc2025084044

Copyright: © 2025 by the authors. Licensee MDPI, Basel, Switzerland. This article is an open access article distributed under the terms and conditions of the Creative Commons Attribution (CC BY) license (https://creativecommons.org/licenses/by/4.0/).

1. Introduction

A crucial amount of research has been carried out progressively in the Computer Aided Process Planning (CAPP) area since the computer technology used for process planning was introduced four decades ago. The involvement of CAPP is used for increasing quality more than saving time and decreasing costs. Additionally, CAPP plays a significant function between design and process of manufacturing engineering [1]. The CAPP system provides a digital connection between manufacturing instruction and CAD model. Generally, the planning process involves design data interpretation, sequencing of manufacturing operations, selection of jigs and fixtures, selection of machines and cutting tools, determination of cutting parameters, and optimization of machining cost and time [2,3].

Additive manufacturing (AM) also recognized as 3D printing or rapid prototyping, has developed its popularity in the manufacturing industry. 3D printing has provided an advanced AM process that allows users to produce complex geometrical shapes by utilizing design software. In contrast, it was previously very difficult to produce the complex geometrical shapes by using conventional fabrication process. The use of AM technology is growing extensively, and the public sector continues to push its use [4]. Nevertheless, the 3-axis AM process limitations are analyzed, such as challenges related to the fabrication and strength of large-scale structures [5] and the possibility of multi-axis AM technology is studied, which includes elimination of staircase effect and large-scale manufacturing [6]. To overcome the 3-axis AM process limitations, multi-axis AM is used to build parts via redundant degrees of freedom.

AM is an important element in contributing to Industry 4.0. It can minimize material waste in order to have a huge environmental effect. AM is now available as a disruptive technology to execute the critical task in Industry 4.0. By merging design software and 3D printing hardware, it can be used to produce a complete AM product. Thus, AM processes can be performed automatically by providing instruction through the software and abolishing human labor. The ability to manufacture complex geometries, allow for the customization and fabrication of lighter structures, which are the main advantages of AM [7].

For example, GE Aviation can produce more than 100,000 units of jet engine fuel nozzles by using AM processes. GE can print the nozzle with a 25% lighter weight, and a durability up to 5 times greater than conventional manufacturing [8]. AM allows the nozzle to be fabricated in one piece from 20 separate cast parts that were assembled previously. This would cut the GE manufacturing cost by 75%, saving equal to 3 million USD per aircraft per year. Another use for AM processes is for mass production of various customized medical parts. Around 50 million dental bridges, crowns and copings were produced by utilizing AM process [9].

Materials used in AM must be well-suited with the printing process. Currently, improvement in the printing process requires greater diversity in the material used to print the AM product. There are three categories of material namely biological, electrical and smart materials. The classification of printed materials depends on their application [10].

There are a variety of types of 3D printing technologies and each type has its own targeted application [11]. Stereolithography (SLA), Multi Jet Fusion (MJF), Fused Deposition Modeling (FDM) and Selective Laser Sintering (SLS) are common technologies of 3D printing. SLA and FDM are the most extensively used among these techniques. The 3D printing process has been separated into three phases which are design, slicing and print phases [12].

3D printing has continued to develop over the years and become one of the primary promising technologies in Industry 4.0 [13]. Nevertheless, the majority of printing processes are less efficient since users have to convert the 3D CAD model into machine language like G-code for printing the model or deciding the suitable type of printing process to be used. Therefore, this paper aims to overcome the limitation by studying an integrated CAD/CAM system that can be used for Computer Aided Process Planning (CAPP) to interact or automate the printing process towards Industry 5.0.

2. Methodology

The study started from the design process and finished with printing process for generating additive manufacturing products by computer aided process planning.

2.1. Designing 3D CAD Models for Additive Manufacturing Products

All additive manufacturing products for 3D, 4D and 5D printing were modeled using SolidWorks. Each product is designed by having specific design characteristics for each type of printing process. Table 1 shows design characteristics applied for each type of printing process.

Table 1. Design characteristics for additive manufacturing products.

Type	3D Printing	4D Printing	5D Printing
Design Characteristics	Product has to maintain as a static or fixed shape. The product should be able to be printed by a printer, i.e., up to 3 degrees of freedom.	Product can transform itself into another structure due to the effect of external factors like temperature, heat or light. The product applies smart material such as shape memory polymer.	Product contains complex freeform surface that hard to be printed by the 3D printer. The 5D printer needs to be used since it has 5 degrees of freedom.

2.2. Generating 3D/4D/5D Printing Process Planning by a Creation of Macro

The algorithm for generating 3D/4D/5D printing process planning is started by opening SolidWorks software (SW2023). Then, a new macro is selected from the toolbox. The macro is employed to execute the algorithm since it has a nature of script which can allow user to perform the process planning operations in SolidWorks automatically or with user interaction.

An algorithm is created to open the CAD file for the selected part, i.e., any type of additive manufacturing product. There are two methods for opening the part file which are (i) require user interaction and (ii) fully automated. Algorithm 1 and Algorithm 2 show the comparison between the two methods for opening the part file.

User interface is created for the user has to interact by filling in the information in the macro. For the user interface, the decision to determine the type of printing process is made according to the information given by the user, as shown in Figure 1. The user has to key in numbers for material as given in the instruction and number of datums as presented in the engineering drawing. For making this decision, the type of printing process is determined in the algorithm based on requirements as follows:

(i) If the number of materials is equal to 1 and the number of datums is equal to or greater than 3; the type of printing process is 5D printing.
(ii) If the number of materials is equal to or greater than 2 and the number of datums is equal to or more than 1; the type of printing process is 4D printing.
(iii) Otherwise, the type of printing process is 3D printing.

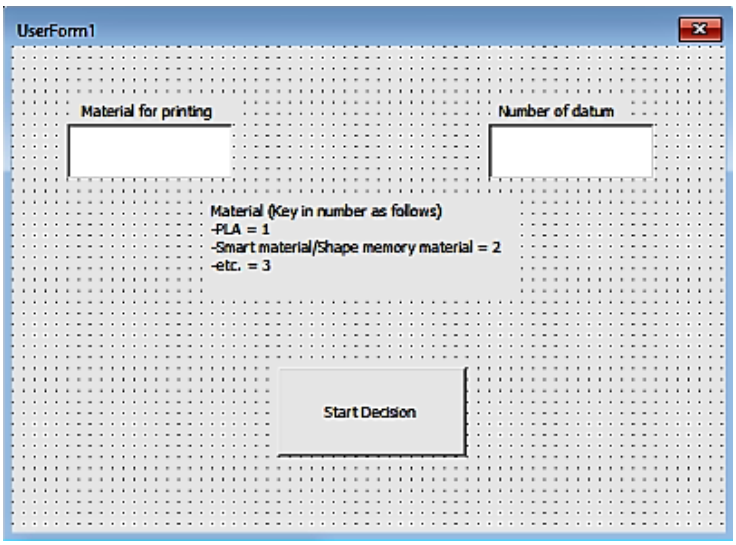


Figure 1. User interface used for making decisions to determine the type of printing process.

Algorithm 1 Required user interaction method for opening the part file

```
Creating variables for SolidWorks application
Creating variables for SolidWorks document
Creating variables for SolidWorks drawing
Declare t1, t2 where t = time
Program main function
Sub main()
    Setting variable of SolidWorks
        Message Box "Please open SolidWorks part file."
      t1 = Now
      t2 = Now + Time Value("0:00:30")
       Do Until t1 ≥ t2
            Do Events
            t1 = Now()
       Loop
    Response = Message Box("File are open?", Yes or No)
        If Response = Yes, Then
            Message Box "Please open drawing for the part."
              t1 = Now
               t2 = Now + Time Value("0:00:30")
                    Do Until t1 ≥ t2
                        Do Events
                        t1 = Now()
                    Loop
        Else
            Continue
        End If
  Response = Message Box("Drawing are open?", Yes or No)
        If Response = Yes, Then
            Message Box "Proceed to next part."
        Else
            Continue
        End If
End Sub
```

Algorithm 2 Fully automated method

```
Creating variables for SolidWorks application
Creating variables for SolidWorks document
Creating variables for SolidWorks drawing
Program main function
Sub main()
    Setting variable of SolidWorks
    Open part file
    Open drawing file
End Sub
```

For example, the number of datums and number of materials for the type of printing process are shown in Table 2. Three different types of products are used in order to test

the developed algorithm for three types of printing process, i.e., 3D, 4D and 5D printing whether it can determine the type of printing process correctly for each product respectively.

Table 2. Number of datums and material for the type of printing.

Type of Printing Process	3D Printing	4D Printing	5D Printing
Number of datums	2	2	5
Number of materials (Shape memory material/Smart material = 1, PLA = 2 or Others = 3)	2	1	2

For printing the AM product, the 3D CAD model file of the AM product needs to be converted to STereoLithography (STL) file for generating G-code. The converting process for 3D CAD model file to STL can be made automatically by employing macro in order to ensure AM process can be performed automatically by abolishing human labor and providing instruction through the software. The algorithm used to convert 3D CAD model file automatically to STL file is shown Algorithm 3.

After the 3D CAD model file is converted automatically to STL file, the slicing process is carried out to convert the STL file into a set of machine instructions namely G-code that can be utilized by the 3D/4D/5D printers. The STL file is imported into slicer software that is Ultimaker Cura 5.7 for generating a G-code file. The FDM method is required for fabricating the product. For the printing process, PLA filament is used as the material. The extrusion nozzle of the printer is fed by the filament. Then, the molten filament is extruded or deposited by the nozzle onto a table base of the printer, and it moves in 3 dissimilar axes or coordinates based on the G-code.

Algorithm 3 Process for converting 3D CAD model file to STL file

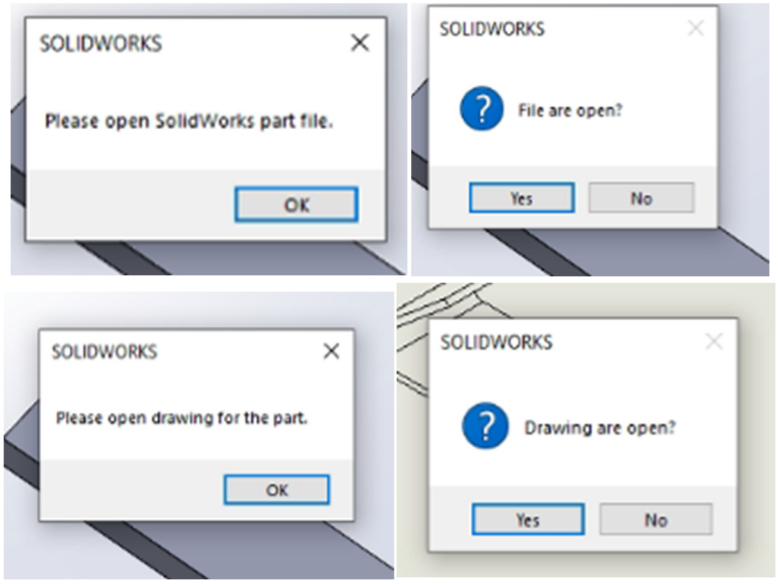
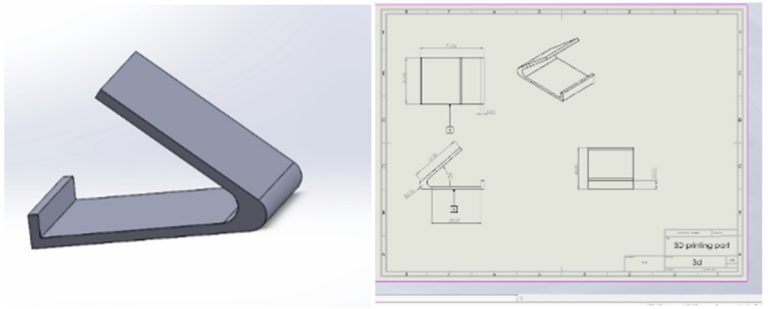
```
Creating variables for Object
Creating variables for SolidWorks application
Creating variable for SolidWorks document
Creating variables for Part
Creating variables for Boolean
Creating variables for Long
Sub main()
    Setting SolidWorks variable
    Open 3D CAD model file
    Save As
End Sub
```

3. Results and Discussion

By using SolidWorks, three additive manufacturing products for 3D, 4D and 5D printing were modeled. Each product has the features for 3D, 4D and 5D printing respectively. As a result, the macro was successfully generated by allowing users to run for opening product files, making decisions and generating G-code operations. When the macro for the method of user interaction was run, a command window popped up to prompt the user to open part the file interactively. The user then has the opportunity to select the respective file. Then, a command window popped up and requested a yes or no response to whether the file was opened or not. When the response is yes, the user is asked to open the engineering drawing file. Nevertheless, the macro ended after the user clicked the

no button. For the fully automated algorithm, the part file and drawing will be opened automatically by the macro. Nevertheless, the user needs to move the part and engineering drawing files to a single folder, since this macro needs a specific file location to open the files automatically. Table 3 shows the result for both algorithms.

Table 3. This Output from the algorithm of opening the product file.

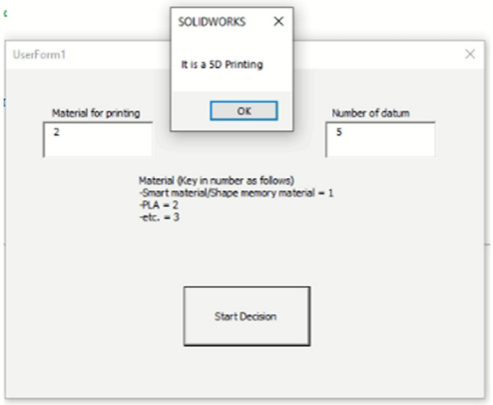
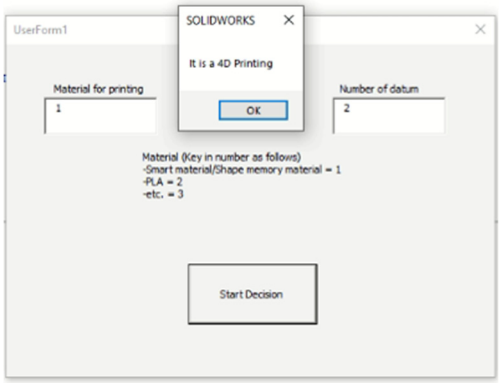
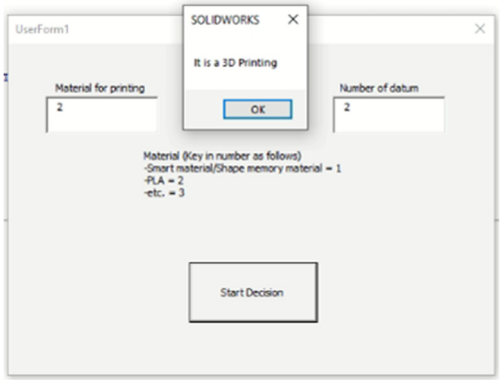
Method	Result
Required user interaction	
Fully automated	

A fully automated algorithm may need less time to open both files, compared to the user interaction algorithm. The algorithm for the fully automated process is short compared to the algorithm for the user interaction.

Table 4 shows results for the algorithm for making decisions to determine the types of printing process that the user wants to use in this program. After the user fills in the form based on the data that the program requires, the result will be shown after the user clicks the 'Start Decision' button.

For the decision-making algorithm, it is used to identify the type of printing process which is suitable for the part. All the parts that are used to test the algorithm have been proven by the program to be the same printing process as the expected printing process. For the 5D printing part, it is decided by the program to undergo a 5D printing process because the 5D part tends to have more datum compared to the 3D part. The 5D part usually has a complex area to print if it does not use support material. According to Haleem and Javaid [14], 5D printing processes can produce curve-shaped products or parts with improved strength. This technology generates parts with curved layers rather than flat layers. Therefore, it is not a 3D printing process. Additionally, this part uses PLA material, so it is again not classified a 4D printing process.

Table 4. Output for making decisions by the algorithm.

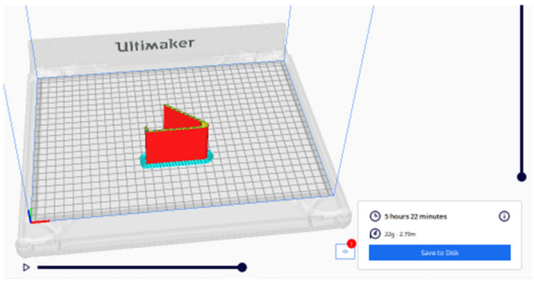
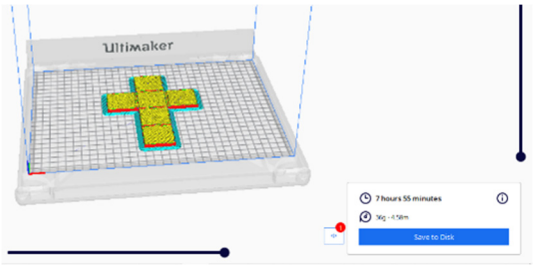
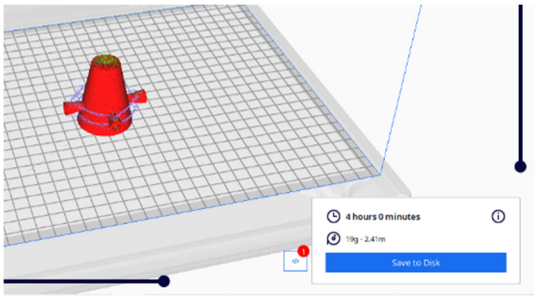
Type of Printing	Result and Explanation
5D printing	 The data that are filled in for 5D part are as follows: Material = 2 and Datum = 5 The decision made by the macro shows that the part should employ 5D printing process. This proves that the part is indeed a 5D printing part.
4D printing	 The data that are filled in for 4D part are as follows: Material = 1 and Datum = 2 The decision made by the macro shows that the part should employ 4D printing process. This proves that the part is indeed a 4D printing part.
3D printing	 The data that are filled in for 3D part are as follows: Material = 2 and Datum = 2 The decision made by the macro shows that the part should employ 3D printing process. This proves that the part is indeed a 3D printing part.

The 4D printing part has also been proven to require a 4D printing process, because 4D printing processes use a smart or shape memory material, which is the same material as the input data (Material 1 = smart material/shape memory material). Compared to 3D printing, material for 4D printing (Smart material) is more flexible, which allows precise material sensitivity configuration with external energy stimuli. Therefore, the program stated that the parts should undergo the 4D printing process.

Furthermore, the program also stated that the 3D printing part should use a 3D printing process. Compared to 5D printing parts, 3D printing parts will have less datum as the parts are not as complex as 5D printing parts although they have the same type of material, which is PLA. Therefore, the program classified that the parts should undergo a 3D printing process. Additionally, this part uses PLA material, so it is definitely not a 4D printing process.

The output from the algorithm for converting 3D CAD model file to STL file has been created automatically. This result is important since the STL file is needed in order to produce the G-code for the printing process. After running the macro, the program opened the part file and automatically created the STL file in the file location that has been inserted in the algorithm. After obtaining the STL file, the G-code can be generated after the slicing process. Pictures in Table 5 show the slicing process and G-code that have been generated in Ultimaker Cura software. It also shows the toolpath for the printing process and the estimated time to complete the printing process.

Table 5. Slicing process and G-code generated.

Printing Process	Slicing Process	G-Code Generated
3D printing		Able to generate G-code
4D printing		Able to generate G-code but it needs further investigation since it is generated based on 3D printing process
5D printing		Able to generate G-code but it needs further investigation since it is generated based on 3D printing process

4. Conclusions

In conclusion, process planning for 3D/4D/5D printing is important to overcome the associated limitations, although the printing process can be operated either fully automated or with user interaction. The creation of this algorithm has brought a benefit to the additive manufacturing process: to become more efficient, while advancing towards Industry 5.0. This preliminary study has produced an algorithm that can be used to determine the type of printing process successfully and converted 3D CAD model file automatically to STL file to be further used for slicing process and generating G-code. Based on the testing for the algorithm, it has been found that the algorithm is capable to produce additive manufacturing products completely by utilizing an integrated CAD/CAM system with 3D printing and extended up to 5D printing simulations. For future studies, G-code generation for 4D printing and 5D printing need further investigation since both are generated based on 3D printing process.

Author Contributions: Conceptualization, I.N.I. and M.S.A.M.; methodology, I.N.I. and M.S.A.M.; software, I.N.I. and M.S.A.M.; validation, I.N.I. and M.S.A.M.; formal analysis, I.N.I. and M.S.A.M.; investigation, I.N.I. and M.S.A.M.; resources, I.N.I. and M.S.A.M.; data curation, I.N.I. and M.S.A.M.; writing—original draft preparation, I.N.I.; writing—review and editing, M.S.A.M.; visualization, I.N.I. and M.S.A.M.; supervision, M.S.A.M.; project administration, M.S.A.M.; funding acquisition, M.S.A.M. All authors have read and agreed to the published version of the manuscript.

Funding: This research received no external funding.

Institutional Review Board Statement: Not applicable.

Informed Consent Statement: Not applicable.

Data Availability Statement: The datasets presented in this article are not readily available because the data are part of an ongoing study.

Acknowledgments: The authors would like to thank the School of Mechanical Engineering, Engineering Campus, Universiti Sains Malaysia for supporting this study.

Conflicts of Interest: The authors declare no conflicts of interest.

References

1. Kataraki, P.S.; Abu Mansor, M.S. A novel classification of freeform volumetric features and generative CAPP approach for milling machine selection. *Int. J. Adv. Manuf. Technol.* **2018**, *98*, 985–1009. [CrossRef]
2. Zubair, A.F.; Abu Mansor, M.S. Auto-recognition and part model complexity quantification of regular-freeform revolved surfaces through delta volume generations. *Eng. Comput.* **2020**, *36*, 511–526. [CrossRef]
3. Kataraki, P.S.; Abu Mansor, M.S. Automatic designation of feature faces to recognize interacting and compound volumetric features for prismatic parts. *Eng. Comput.* **2020**, *36*, 1499–1515. [CrossRef]
4. Jiang, R.; Kleer, R.; Piller, F.T. Predicting the future of additive manufacturing: A Delphi study on economic and societal implications of 3D printing for 2030. *Technol. Forecast. Soc. Chang.* **2017**, *117*, 84–97. [CrossRef]
5. Yao, Y.; Cheng, L.; Li, Z. A comparative review of multi-axis 3D printing. *J. Manuf. Process.* **2024**, *120*, 1002–1022. [CrossRef]
6. Tang, P.; Zhao, X.; Shi, H.; Hu, B.; Ding, J.; Yang, B.; Xu, W. A review of multi-axis additive manufacturing: Potential, opportunity and challenge. *Addit. Manuf.* **2024**, *83*, 104075. [CrossRef]
7. Korpela, M.; Riikonen, N.; Piili, H.; Salminen, A.; Nyrhilä, O. Additive Manufacturing—Past, Present, and the Future. In *Technical, Economic and Societal Effects of Manufacturing 4.0*; 2020; pp. 17–41. Available online: https://link.springer.com/book/10.1007/978-3-030-46103-4 (accessed on 21 May 2024).
8. Khorram Niaki, M.; Nonino, F.; Palombi, G.; Torabi, S.A. Economic sustainability of additive manufacturing: Contextual factors driving its performance in rapid prototyping. *J. Manuf. Technol. Manag.* **2019**, *30*, 353–365. [CrossRef]
9. Oettmeier, K.; Hofmann, E. Additive manufacturing technology adoption: An empirical analysis of general and supply chain-related determinants. *J. Bus. Econ.* **2017**, *87*, 97–124. [CrossRef]
10. Kim, Y.; Yuk, H.; Zhao, R.; Chester, S.A.; Zhao, X. Printing ferromagnetic domains for untethered fast-transforming soft materials. *Nature* **2018**, *558*, 274–279. [CrossRef] [PubMed]

11. Muthe, L.P.; Pickering, K.; Gauss, C. A Review of 3D/4D Printing of Poly-Lactic Acid Composites with Bio-Derived Reinforcements. *Compos. Part C Open Access* **2022**, *8*, 100271. [CrossRef]
12. Nandi, C.; Caspi, A.; Grossman, D.; Tatlock, Z. Programming language tools and techniques for 3D printing. In Proceedings of the 2nd Summit on Advances in Programming Languages (SNAPL 2017) Leibniz International Proceedings in Informatics (LIPIcs), Asilomar, CA, USA, 7–10 May 2017; Volume 71.
13. Golovianko, M.; Terziyan, V.; Branytskyi, V.; Malyk, D. Industry 4.0 vs. Industry 5.0: Co-existence, Transition, or a Hybrid. *Procedia Comput. Sci.* **2023**, *217*, 102–113. [CrossRef]
14. Haleem, A.; Javaid, M. Future applications of five-dimensional printing in dentistry. *Curr. Med. Res. Pract.* **2019**, *9*, 85–86. [CrossRef]

Disclaimer/Publisher's Note: The statements, opinions and data contained in all publications are solely those of the individual author(s) and contributor(s) and not of MDPI and/or the editor(s). MDPI and/or the editor(s) disclaim responsibility for any injury to people or property resulting from any ideas, methods, instructions or products referred to in the content.