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Research Article

Characterization of Functionality and Deterioration Concepts in Additive Manufacturing Technology with Application to Fused Filament Fabrication Technique

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Abstract

Objective: In order to industrialize Additive Manufacturing (AM), we proposed in previous works to elaborate Industrialization Standard for AM (IS4AM). The IS4AM is a promising concept but remains very conceptual and requires more empirical validation and implementation strategies to the real-world applications. For example, several issues such as defect, fault, failure and damage can affect the AM progress at several levels: AM process, design and resulting products (quality, usability …), even the machine elements and the surrounding environment. So, we propose here a generalized concept called deterioration to overcome these issues considering real-world applications in AM technology.

Methods: In order to understand the deterioration concept considering AM as a specific technology to deal with, functionality concept should be first treated. Next, we select an AM machine (Adventurer 3+, manufactured by FLASHFORGE) based on Fused Filament Fabrication (FFF) as a simple and common AM technique with the object of treating the different probable functions and their classifications. After that we define a generalized concept called deterioration to cover the different problem cases in this specific technology. For example, in certain AM applications, a small defect may lead to a rejection of the final product by the customer, which forms a big obstacle in the industrialization of this technology. In addition, damage of machine elements and surrounding environments is considered here as an additional issue when comparing to the three components (defect, fault and failure) treated in the other industries.

Results: It has been found that functionality and deterioration concepts in AM are highly related to uncertainty existence, which leads to additional warnings (difficulties) when characterizing these concepts. Classification systems for functionality and deterioration levels in AM are next clarified to provide a deep relevance to AM industrialization challenges. The different illustrative examples for pure and composite Polylactic Acid (PLA) materials represent here various deterioration degrees and classes, especially when dealing with composite PLA ones.

Conclusion: Uncertainty plays an important role in preventing the industrialization of AM technology. Regarding several industries, we proposed a new concept called deterioration as a novel framework to be compatible with AM technology in order to reduce the uncertainty effects which paves the way to establish the IS4AM.

Keywords: additive manufacturing, additive manufacturing industrialization, fused filament fabrication, uncertainty, maintenance

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1 INTRODUCTION

In the automative industry, we seek to obtain reliable and safer systems with longer life by reducing the failure likelihood and improving the reliability levels. This way, the concept of Failure Modes and Effect Analysis (FMEA) has been used in the process of failure mode/mechanism identification[1]. However, in Additive Manufacturing (AM) technology, identification of failure modes is much more complicated and needs to deal with several issues such uncertainty. In addition to uncertainty, maintenance plays an important role in the industrialization of this technology from several points of view such as economy, safety, operation and environment. Two maintenance methods have been used significantly across the world. The first one is called Reliability-Centered Maintenance (RCM), which had its origins in the airline industry, and the second one is called Total Productive Maintenance (TPM), which had its origins in manufacturing[2]. The TPM is employed for production strategies which have been already industrialized, whereas RCM can be integrated into AM technology in order industrialize this technology[3,4]. The different existing RCM standards can help in giving effective ideas in defining the different concepts regarding functionality, deterioration (defect/ fault/ failure/ damage) and resulting consequences. In existing maintenance standards, several criteria are determined to perform different maintenance tasks such as cleaning, lubrication, repairs and replacements. So, the maintenance industry utilizes these standards with the object of maintaining efficient, reliable, and safe operations. In our previous work[3], NAVAIR 00-25-403 (2016)[5] has been selected regarding four important criteria: 1) Failure consequences categories, 2) Hidden failures treatment, 3) Different consequences management, and 4) Decision diagrams. Regarding the RCM notion, many standards have been established where the RCM strategy is customized to different application areas[6]. In literature, a big number of RCM standards can be found such as MIL-STD-2173 (1986)[7], IEC 60300-3-11 (IEC 1999)[8], USACERL TR 99/41 (USACERL 1999)[9], NASA (2000)[10], DEF-STD 02-45 (DEF 2000)[11], SAE JA 1012 (SAE 2002)[12], ABS (2003, 2004)[13,14], NAVAIR 00-25-403 (NAVAIR 2005)[15], MSG-3 (2007)[16]... Each one of these standards is related to specific industrial issues with the object of enhancing the capability of making effective and efficient decisions during the development of maintenance tasks[17]. These standards are always in progress. A maintenance department must continually adapt their strategies with the purpose of determining which standards are most applicable to their unique requirements. In Ahmadi A's studies[17,18], the RCM strategy by MSG-3 standard was chosen with the object of providing information for aviation industry. In order to use this standard for AM technology, we need to elaborate a specific standard form. Some ideas and proposition have been already proposed in our previous works[19,20] in order to pave the way to elaborate an Industrialization Standard for AM (IS4AM). In addition, effective techniques such as optimization and Artificial Intelligence (AI) should be used to overcome several challenges such as execution inaccuracies and material anisotropy[21]. Our previous studies and findings focused on the main challenges when dealing with FFF technique, especially uncertainty issues. Several application fields such as dentistry, decoration, robotics …, were treated to provide solutions and recommendations for overcoming challenges. However, in this work, we focus on the redefinition of different concepts related to functionality and deterioration. And some examples are presented to support the proposed definitions. A Fused Filament Fabrication (FFF) machine is used to explain explicitly the different functionality and deterioration problems. In addition, curves and diagrams are used to relate our industrial experience to academic outcomes. Finally, future perspectives and conclusions are presented to provide several applicable ideas to integrate advanced techniques being helpful in the industrialization of this technology.

2 MATERIALS AND METHODS

2.1 Used FFF Machine

The characterization of the functionality and deterioration concepts is carried out using Adventurer 3+ by FLASHFORGE Company. This machine shown in Figure 1 uses FFF technique where the extruder has the objective of drawing the filament from the spool, melting it and pushing it through a nozzle till the building platform (BPF). Some important parts of the machine are illustrated in this figure where several issues may appear, especially at the level of the tube connection which can be the first part of the machine to be damaged and leads to a separation of the filament guide tube. So, the small black caoutchouc tube joint shown in Figure 1 can be damaged due to fatigue when fabricating complex and/or pretty large-format products requiring high printing time. In this machine, filament feeding wheels consisting of capstan and driven wheels continue to push filament material to the outside but not to the extruder[22,23]. Unfortunately, the current mentoring screen illustrated in Figure 1 only reacts when filament ends (a message appears: Filament Error). Despite the possibility of several consequences such as stopping the extrusion

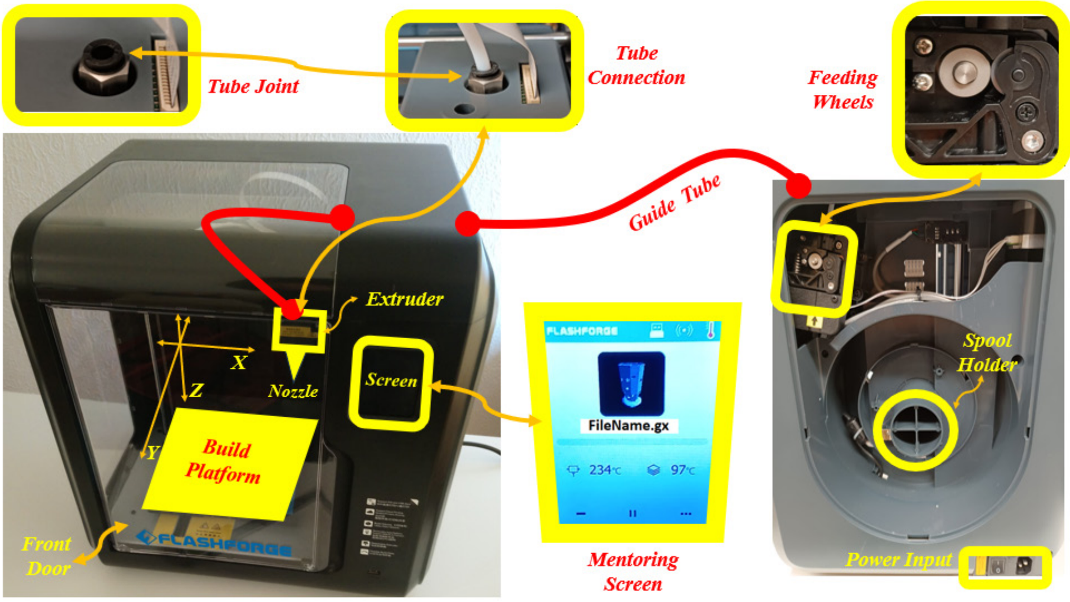

Figure 1. Details about the Used Adventurer 3+ Based on FFF Technique.

process, opening the front door, troubling in sliding slots and so on, the mentoring screen does not provide any signals for all these kinds of consequences. This kind of event and consequences are characterized in this work as an essential step to industrialize AM technology, especially when dealing with the FFF technique.

2.2 Characterization of Functionality Concepts

2.2.1 Definitions

The functionality of equipment or something can be seen as the purpose for which it is made or simply what it can do. As it is mentioned in Skågeby J's study[24], functions are generally designed to perform a delimited task as efficiently as possible. As such, the small function is a logical and deterministic – it yields a predictable result. A complex system usually consists of a big number of functions. As mentioned, this larger aggregated set of functions is what can be described as functionality. Additionally, in order to provide overview and control of functionality, a (graphical) user interface is usually required. So, while functions are 'machinic' in the sense that they must generate a consistent result when invoked, a complex program or service can be utilized and experienced rather differently depending on the user, the task and the context. Thus, when discussing the full meaning of functionality, it is also necessary to widen the perspective to include concepts from interaction design and user experience research[24]. It can help us to understand the product design and manufacturing with the objective of users' (operators') satisfaction[25]. A classification of different functions should be provided to figure out a specific area[26]. In this paper, we define some necessary functions to perform a complete 3D printing process where the studied machine (Adventurer 3+) performs several functions in order to complete its tasks.

2.2.2 Function Classifications

Figure 2 shows the classification of the different functions with some examples about each one. These classifications are explained in this section and supported by some illustrative examples in Section 3.

2.2.2.1 Essential Functions

These functions are necessary to fulfil the intended purpose of an item. So, they are simply the reasons for using the corresponding item. For example, an essential function of an extruder in a 3D printer is to extrude melted material. The function of the extruder is to draw the filament from the spool, melt it and push it through a nozzle on the BPF.

2.2.2.2 Auxiliary Functions

These are the functions that are needed to support the essential functions. A failure of an auxiliary function may in numerous cases be more critical than a failure of an essential function. The feeding system has an auxiliary function to support the extruding function in a 3D printer. When feeding wheels don't work properly, a big perturbation of material extrusion can occur, which leads to failure and/or bad quality of the final product[19].

2.2.2.3 Protective Functions

These functions are intended to protect people, equipment and/or environment. Isolating functions in AM are an example of people, equipment and surrounding environment protection. The front door of the used AM machine shown in Figure 1 represents an important example of this kind of function regarding odors and other failure consequences.

2.2.2.4 Information Functions

These functions seek to provide information about the AM operation comprise condition monitoring, various gauges and alarms etc. Printer's touch screen is an example to show the temperatures, remaining time ...etc. The importance of this function should be considered at the preprocess stage such as parameter initialization,

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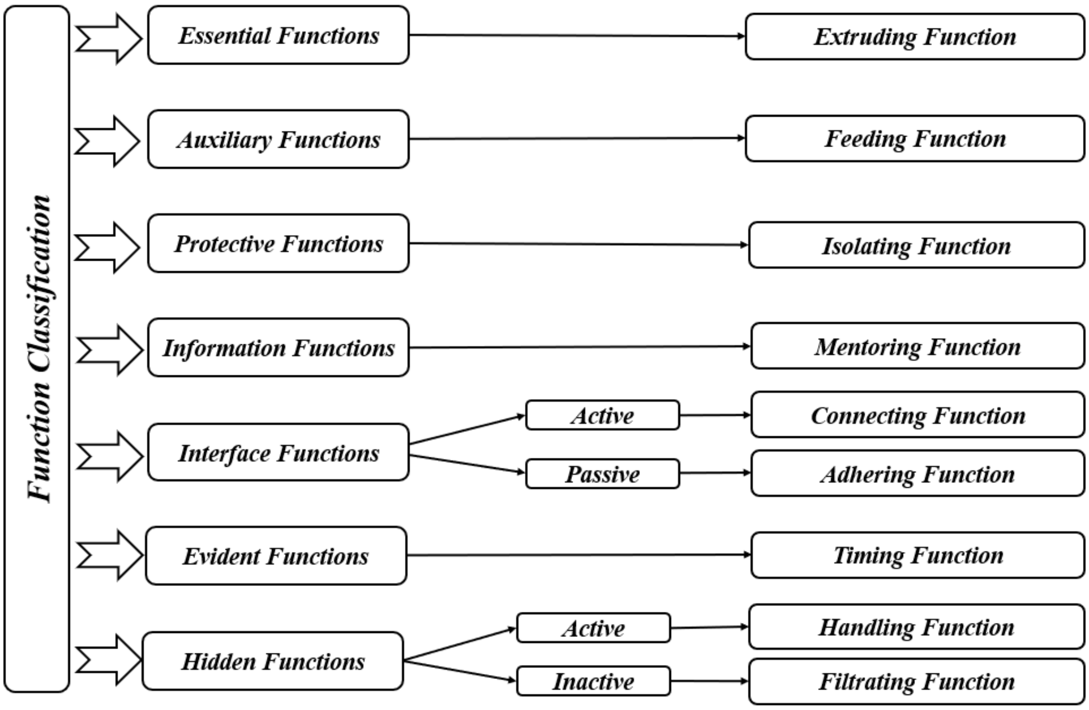

Figure 2. Function Classifications Supported by Practical FFF Function Examples.

especially preheating stage. At an advanced stage, the AI-driven framework enables early problem prognosis (defect, fault, …), minimizing disruptions and the likelihood of substandard output[27].

2.2.2.5 Interface Functions

These functions generally are related to the interfaces between the item in question and other items. The interfaces are divided here into active or passive functions. Considering the used AM machine, connecting function representing the tube and its ends is an active type, while a passive interface is for example present when an item is a support or a base for another item such as adhering function between the printed part and the BPF.

2.2.2.6 Evident Functions

These functions can be also known as online functions, where an evident function is one whose failure will be evident to the user (operator) during the performance of normal duties. They can be operated either continuously or so often that the user has current knowledge about their state. For example, timing functions represent evident functions where the user knows the remaining time to end the AM process.

2.2.2.7 Hidden Functions

These functions can be also known as offline functions. They are used intermittently or so infrequently that their availability is not known by the user (operator) without some special check, test or upon demand[28]. A hidden function is one whose failure will not be evident to an operator during the performance of normal duties. This way, several protective functions are hidden functions. The hidden functions can be divided into two kinds: active and inactive functions. The first kind is normally active but gives no indication to the operator if it ceases such as data handling function, while the second kind is normally inactive, so that the user cannot know whether it will be available when it is needed such as filtering function. For example, an AM process can be randomly stopped at certain times and continue without any indication. This leads to a perturbation of material extrusion, which represents a defect or even fault in the final product (ex. perturbation in material distribution in certain points or areas in the final product).

Finally, we must mention that certain functions can be classified according to the AM machine used. For example, when dealing with heating functions, additional information can be added to the mentoring screen to show the temperatures at the preheating stage and during the AM operation as well. In addition, speeding functions make the mentoring role very complicated when needing to provide information about the different speeds (ex. print, travel and/or retraction speeds). So, the classification of the present functions in Figure 2 can be varied according to the AM machine used.

2.3 Characterization of Deterioration Concepts

2.3.1 Definitions

In AM technology, deterioration is related to several things: product, production, machine and environment. It can be represented by defect, fault, failure and/or damage cases. In general, defects can affect the quality of the final product without affecting its functionality. However, fault affects the functionality of the final product. So, the product

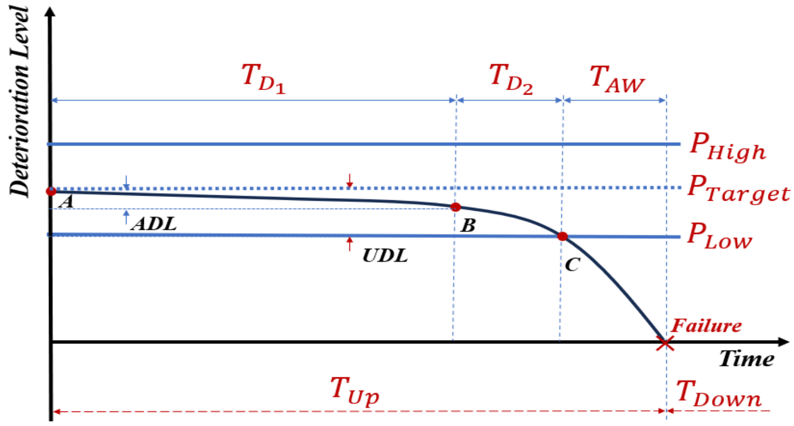

Figure 3. Proposed Performance Curve for AM System.

is not able to perform its function due to the existence of partial fault, hidden fault … [2]. In AM, the fabrication continues until the end in the case of existence of defect and/or fault. On the other hand, failure can be represented by the termination of successful AM processes. The last deterioration level is damage which can be sometimes seen as a consequence of failure or faults such as nozzle clogging. In other cases, it can occur due to other errors such as human errors.

In order to deal with the last two levels (failure and / or damage), we define the AM machine as a unit. The AM machine presented in Figure 1 can be considered as a unit composed of several systems such as extrusion system. This extrusion system contains several subsystems such as the extruder base which contains several equipment such as nozzle. This hierarchy should be defined clearly to apply advanced maintenance strategies to help in industrializing AM technology. Before our generalization to deterioration concept, we focus on failure concept and its effects in the next subsection, since it forms an important aspect of deterioration studies in many industries.

2.3.2 Failure and its Effects

2.3.2.1 Definitions

The definition of failure varies according to different sectors. For example, when dealing with machine maintenance, it is considered as the termination of the ability of an item (part, component, equipment …) to execute a required function. It can be characterized by the following terms:

Failure mode (or scenario) which is a specific physical condition or state that causes a particular functional failure. In other words, it is the manner in which an item fails.

Failure cause which is the reason of the failure mode to occur.

Failure detection which is to describe the existing means and methods by which the effects can be detected.

Failure effect which is the result of a functional failure on surrounding items.

Failure consequences which are the results of a process of failure. They are outcomes or effects of failures as logical results or conclusions. A consequence can be defined as the result of a failure such as damage to machine elements and/ or surrounding environment. Types of consequences can be represented by several measurements such as economy, environment, delay, cancellation, customer dissatisfaction, loss of market, equipment damages …

Failure mechanism which is a physical, chemical or other process that has led to failure. A common interpretation of this term can be seen as the immediate cause of an indenture.

Failure analysis which is the manner of collecting and analyzing data to determine the cause of a failure.

2.3.2.2 Failure Classifications

Failure is the termination of the ability of an item to execute a required function. Any identifiable deviation from the original state that is unsatisfactory to a particular user. The incapability of any asset to do what its user wants it to do. However, error is a discrepancy between a computed, observed, or measured value or state and the true, specified or theoretically corrected value or condition[29]. Figure 3 shows the proposed performance for AM system, where the deterioration level changes over the time from the performance target P_{Target} to the failure case. Several points can define this curve considering the deterioration levels from A. The acceptable deviation interval between the higher performance limit P_{High} and the lower one P_{Low}. The distance between the performance curve and the performance target P_{Target} is called ‘ERROR’. B is a point existing in the acceptable deviation interval (or Acceptable Deterioration Level (ADL)), while C is found at the intersection of the performance curve with the lower boundary P_{Low}. After this point, the region can be considered as an Unacceptable Deterioration Level (UDL) because it exceeds the limit. Here, there is a need to perform maintenance action in order to overcome this kind of deterioration [19].

Figure 4 shows the failure classifications and a related function example of each classification for the AM machine used here. A single illustrative example supports each case, except when dealing with multiple failure cases. In this

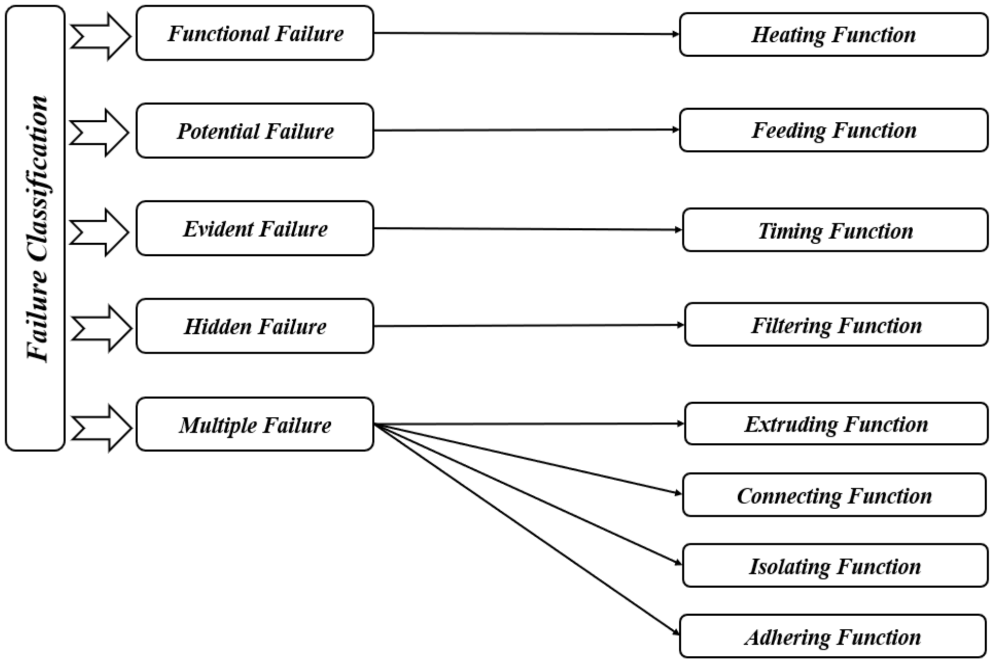

Figure 4. Failure Classifications Supported by FFF Function Examples.

section, the explanation of each case is supported by several failure cases taking our practical AM experiences into account.

2.3.2.2.1 Functional Failure

It concerns the inability of an item to perform a specific function within the user's specified desired performance limits. Functional failures can show a total or partial loss of function. There is a decrease or increase in the performance of certain parameters and also an intermittent operation of this function. For example, extrusion function is related to feeding wheels. The perturbation of the feeding rate can highly affect the extruding functions (e.g. decrease or increase of layer thickness due to under- or over-extrusions, respectively[30]).

2.3.2.2.2 Potential Failure

It can be represented by an identifiable and measurable state that indicates an impending functional failure. For example, the deterioration level of the flow of melted material in the extruder can be represented in Figure 5A and 5B. Figure 5A represents the deterioration level for several printing cases for pure PLA material where the dashed line is used here to indicate several printing operations or long printing time. Here, we start with healthy level $L_{Healthy}$ until level L_{Minor} where the sign of clogging becomes detectable (sounds, change of the printed layer thickness). Here, maintenance actions should be scheduled in order to avoid any probable defect cases. However, at level L_{Major}, a maintenance action becomes mandatory, otherwise we may meet fault cases due to extrusion perturbation. In Figure 5B, the curve represents composite wood fibers with PLA for a single printing case. For long printing time (T_{Up}), a nozzle clogging may occur even for the same printing process (ex. due to unsuitable size of knots or accumulation of several knots), while for a short printing time, it is possible to meet one of the following levels: L_B, L_C, L_D, L_E until clogging. From L_A to L_B, we have smooth flow time (T_F), while the deterioration levels may quickly increase at L_C, L_D, L_E until Clogging point. At level L_C, a small decrease (under-extrusion) in the melted material flow starts, where the printing layer is still acceptable, and the deterioration effect is not detectable. In other words, the change of layer thickness is not detectable. However, between the levels L_D and L_E, we define minor and major deterioration levels, respectively. Here, maintenance actions are needed to avoid affecting the quality of the final products. The detection of deterioration levels can be detected in several ways such as acoustics/vibrations, change of printed layer thickness ... It is better to take an action before additional damages or failures. Figure 5B can be totally different when unacceptable knots exist in the raw filament, which can happen due to uncertainty matter.

We have to mention that when dealing with pure PLA material, there is no need to clean the nozzle at each use. It is only recommended to unload filament after each printing operation in order to avoid solidification of the residual impurities in the thin canals of the nozzle. A nozzle cleaning action is needed when detecting any change in the printed layer thickness or in the mechanical properties of the final product.

2.3.2.2.3 Evident Failure

An evident (or online) function termination is called "evident failure" which can become clear to the users or operators while performing their normal duties. All evident failures are analyzed as single failures without considering

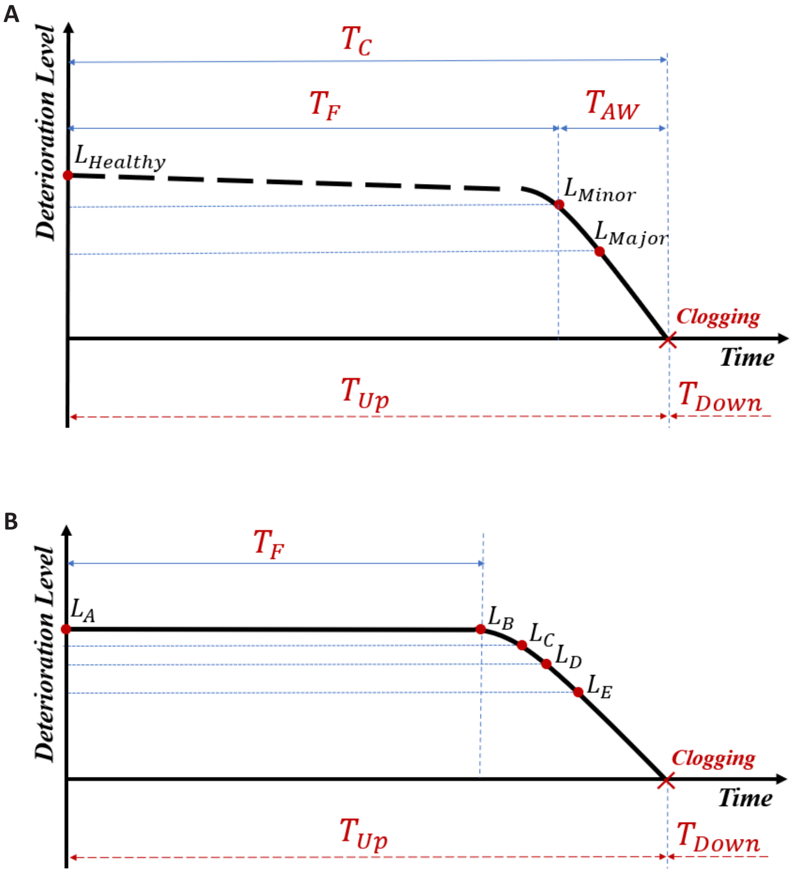

Figure 5. Curve of Deterioration Levels of Nozzle Clogging Circumstances for (A) pure PLA materials, and (B) Composite PLA Materials.

their consequences. For example, remaining time can be different depending on the environmental conditions. In cold weather, there is a need to heat the extruder and the BPF to be suitable for the printing process. In this case, the remaining time on the mentoring screen (Figure 1) will not provide correct information due to certain delays in order to meet the required temperatures which can lead to an interruption in production.

2.3.2.2.4 Hidden Failure

The termination of the inability to carry out a hidden (or offline) function is called a "hidden failure". Here, this failure is not evident to the users or operators while performing their normal duties. For example, the failure of a filtration system containing air filter and outlet represents a hidden failure case which affects the interaction with the environment. To maintain its effectiveness and availability, maintenance actions are frequently needed[31].

2.3.2.2.5 Multiple Failure

It is considered as a combination of a hidden failure plus a second failure or other events that make the hidden failure evident. For example, when overloading a nozzle (e.g. long printing time), a cumulation of material impurities can occur. In certain cases, several kinds of failure can happen: Failure of extruding function leads to failure of AM process; Failure of connecting function leads to breaking the connection end of the tube which leads to the flow of filament outside its trajectory; Other probable failures concern the isolating function (opening the front door) and may also remove the BPF from its sliding base.

2.3.3. Deterioration Categories

Figure 6 shows the different classifications of deterioration categories considering single and multiple categories. A single defect, fault, failure or damage can be considered as a Single Deterioration Category (S.D.C.), while when at least two of them occur, a Multiple Deterioration Category (M.D.C.) should be considered. A single defect case is classified as the 1st class of an S.D.C., which can be acceptable in certain AM areas. However, a single fault case, a single failure case and a single damage case are classified as the 2nd, 3rd and 4th classes of an S.D.C, respectively. These classes are not acceptable in all AM areas and their unacceptability is related to quality and costs. On the other hand, when dealing with M.D.C., multiple deterioration criteria can be found. A multiple defect case is considered as a 1st class of an M.D.C., which can be also acceptable in certain AM areas. For example, when the product has more than one defect, it can be acceptable (special cases). However, a multiple fault/defect case can be seen as a multiple fault case with or without defect(s) is considered as a 2nd class of an M.D.C where neither failure nor damage should exist. A multiple failure/ fault/ defect case can be seen as a multiple failure case with or without fault(s) and/ or defect(s) is considered as a 3rd class of an M.D.C where no damage should exist. Finally, a multiple damage/ failure/

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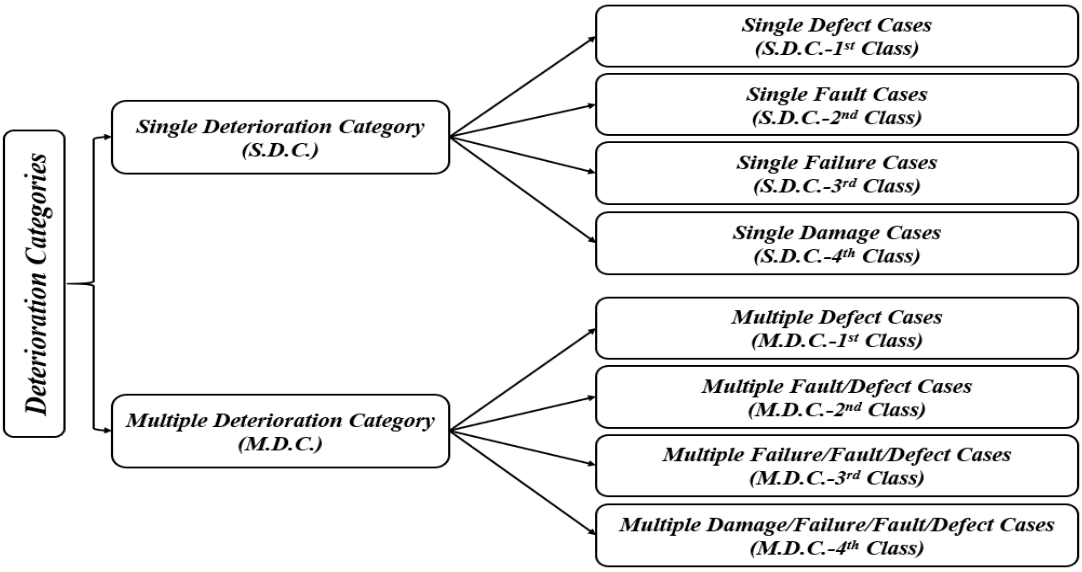


Figure 6. Deterioration Categories Considering Single and Multiple Cases.

fault/ defect case can be seen as a multiple damage case with or without failure(s), fault(s) and/or defect(s) is considered as a 4th class of an M.D.C. The last case is the most dangerous case where equipment damage exceeds the printed part itself and leads to several consequences. These classifications (1st, 2nd, 3rd and 4th) can help in determining risk levels when dealing with FMEA and/or FMECA (Failure Modes, Effect and Criticality Analysis) strategies[4,32-34].

2.3.3.1 Safety Effect Category

The safety effect category must be approached with the understanding that a task is necessary to ensure safe operation. For example, human health and security represents an important matter and any disturbance such as isolating system damage should be avoided with high priority. Filament cover in the used machine (Figure 1) should be controlled before the beginning of the AM process to ensure that the filament is located correctly on the spool holder during the AM process.

2.3.3.2 Operation Effect Category

The operation effect category must be approached with the understanding that a task is essential to ensure continuous operation. For example, nozzle cleaning should be prioritized to ensure the printing continuity and to avoid any probable delay. For certain material, this cleaning should be carried out at the preparation stage for each AM process. Figure 5B shows the deterioration levels for composite PLA material such as wood fibers with PLA. In order to avoid nozzle clogging, it is recommended to clear the nozzle at each AM operation.

2.3.3.3 Environment Effect Category

The environment effect category must be approached with the understanding that a task is required to ensure a safe environment, especially workers' health. For example, it is important to prevent any damage of filtering equipment to prevent the fusion of non-desirable odors. The friendliest material is pure PLA material, however, when mixing this material with other components such as wood fibers, it may lead to several health problems. So, the air filter and outlet should be controlled frequently, and maintenance should be scheduled when there is a need.

2.3.3.4 Economy Effect Category

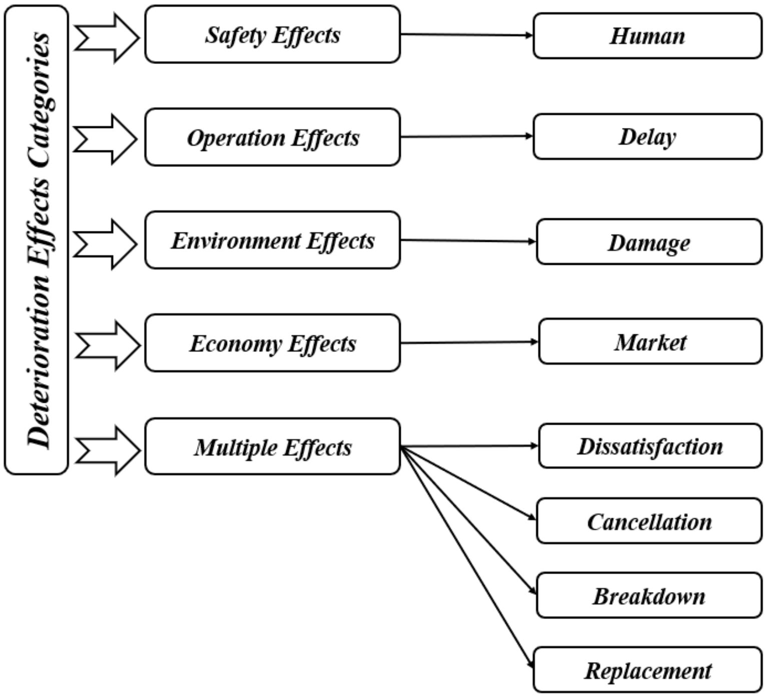
A task is desirable if the task costs are less than the repair costs. Sometime, preventive maintenance actions such as replacing certain equipment leads to high costs relative to the value of the final products. In this case, it is better to analyze the market needs before scheduling certain preventive tasks such as replacing the nozzle or even the extruder. In addition, when fabricating composite PLA materials, repetitive cleanings of the nozzle affect its connection with the extruder. This connection can be damaged and lead to the change of the extruder and its different connections with the other machine elements. In this way, the repair costs can be much higher than the task costs. In addition to the task costs, it is important to take the quality of the manufactured products into account in order to decide whether the repair actions are needed or not.

2.3.3.5 Multiple Effect Category

Failure may lead to many consequences at several levels: economy, safety, operation ... So, a task is desirable if it reduces the failure consequences to an acceptable level. As shown in Figure 7, the consequences can also be represented by customer dissatisfaction which leads to the cancellation of production. In addition, the breakdown of production yields to replace certain equipment (machines) when restarting with new demand. So, several effects can appear as shown in Figure 7: dissatisfaction, cancellation, breakdown and replacement.

3 RESULTS

In this section, we present some real deterioration cases considering single and multiple deterioration categories. When dealing with single deterioration categories, we classify



igure 7. Deterioration Effect Categories Supported by Practical Examples.

each one (from 1st to 4th classes) and provide its effects (single and multiple). However, for the different examples of multiple deterioration categories, we only present their main effects since the consequences of this deterioration may lead to severe cases. For the following examples, two machines of Adventurer 3 series are used as a printing machine, manufactured by FLASHFORGE. These two types of machines use FFF technique where the maximum build volume is 150×150×150mm and the diameter of used filament is 1.75±0.07mm.

3.1 Examples for Single Deterioration Category

Four cases are presented in this subsection to illustrate the difference between defect, fault, failure and damage cases (from 1st to 4th classes).

3.1.1 Defect Case as 1st Deterioration Class

Figure 8 shows a defect case in a bonbonniere made of composite material (wood fibers and PLA). For this example, during the printing process, the input temperatures of extruder and the BPF are respectively: 210°C and 50°C. The print and travel speeds are respectively: 50mm/s and 100mm/s. The infill density type is linear with 10% density and the nozzle size is 0.6mm. It is true that the AM process has been completed to the end, but the material distribution in certain parts of the product was perturbed as shown in Figure 8B. This reduces the quality of the finished product which can be rejected by the customer in certain uses of this product such as decorative models. Here, it can be considered as a 1st deterioration class with an economy effect. Regarding this product, Figure 8A shows a top view of this product where the product seems to be healthy. So, according to the location of these defects, additional costs for repairing are needed to use the final product. To overcome this difficulty, certain operating parameters and/or the design itself should be modified.

3.1.2 Fault Case as 2nd Deterioration Class

Figure 9 shows a fault case in a pen container made of pure PLA material. For this example, during the printing process, the input temperatures of extruder and the BPF are respectively: 210°C and 50°C. The print and travel speeds are respectively: 60mm/s and 80mm/s. The infill density type is linear with 15% density. The nozzle size is 0.4mm and the weight of the resulting product with the raft structure is 22gr instead of 70gr for a healthy one. The material distribution on the infill structure was not homogeneous due to the effectiveness of the nozzle (part clogging). This can be called the under-extrusion case[30], which highly affects the extrusion process at high printing speeds such as infill regions. So, this non-homogeneity affects the whole product from its raft level to its end as shown in Figure 9. This kind of fault can be considered as a hidden fault since it concerns the infill distribution. It is possible to see the final product as a healthy one, however, when pressing this product even by hand, the fault can appear directly. In addition, when considering the performance curve shown in Figure 3, this case can be located between Point C and Failure Point where maintenance action is mandatory (T_{AW} representing action window). So, it is recommended to clean the nozzle to increase its effectiveness. This case is considered as a 2nd deterioration class with economy effect. It can also be seen as a sign of the necessity to perform maintenance actions to avoid any probable failure or damage in the future.

3.1.3 Failure Case as 3rd Deterioration Class:

Figure 10 shows a failure case in a pen container made

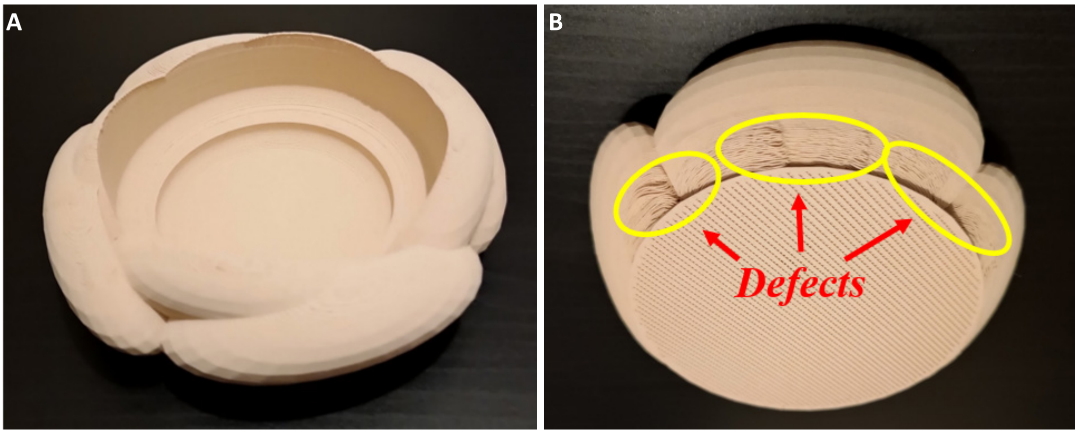


Figure 8. Defect Case in a Bonbonniere Made of Composite Material (wood fibers and PLA). (A) Top view and (B) Bottom view.

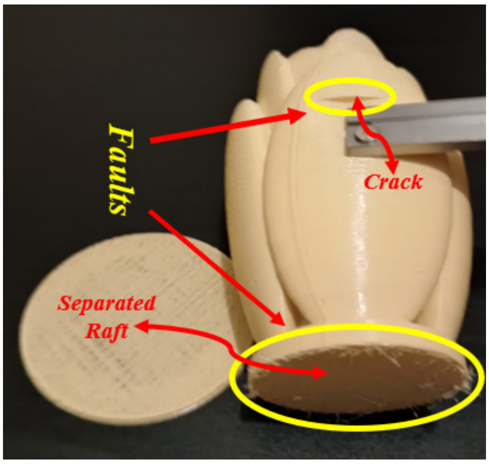


Figure 9. Fault Case in a Pen Container Made of Pure PLA Material.

of pure PLA material using Adventurer 3. For this example, during the printing process, the input temperatures of the extruder and the BPF are respectively: 230°C and 100°C. The print and travel speeds are respectively: 60mm/s and 80mm/s. The infill density type is honeycomb with 15% density and the nozzle size is 0.4mm. The total height of this pen container should be 83.65mm including the raft thickness (1.55mm). However, after almost 10mm of printing a failure represented by the raft separation (due to adhesion problem in the BPF) occurred. The total printing time needed was more than 3 hours, while the process stopped after more than 2 hours due to this failure occurrence. The material extrusion continued after the raft separation and led to the failure situation presented in Figure 10. This case is considered as a 3rd deterioration class with an economy effect (waste of time and materials). In this case, although we increased the temperatures of the extruder and the BPF to increase the likelihood of adhesion during the printing process, a failure occurred. So, the replacement of the building sheet attached to the BPF is recommended to avoid any probable failure in the future.

3.1.4 Damage Case as 4th Deterioration Class

Figure 11 shows a damage case of a filament tube joint whose shape is a modified design of the original one shown in Figure 1. As is mentioned in Subsection 2.1, the tube joint (in Figure 1) can be the first part to be damaged even when printing pure PLA material. Our modified design can be used for more complex composite materials and provide flexibility when cleaning the nozzle. However, when using (wood fiber and PLA), some knots may appear and clog the nozzle which leads to a separation problem as shown in Figure 11. Furthermore, this kind of problem can arise due to many uses (due to fatigue). At the beginning of raft printing, certain forces led to the separation of the filament tube joint. This case is considered as a 4th deterioration class with operation effect where a downtime is needed to rejoin the tube. In this case, nozzle cleaning is needed after rejoining the tube and before the next AM process. When considering this kind of problem as an uncertainty case, it does not follow the performance curve presented in Figure 5B.

3.2 Examples for Multiple Deterioration Category

In this subsection, we present some multiple deterioration cases with consequences where a breakdown needs to perform corrective maintenance actions.

3.2.1 Total Nozzle Clogging Case

Figure 12 shows a total nozzle clogging case where several actions are needed to solve the problem (M.D.C.). The first action is to remove the connection tube which cannot be carried out classically due to the solidification of the material with the impurities. This way, we push the clips and draw down the nozzle applying a suitable tension force to cut the filament (nozzle separation). Several techniques can be used, but this may affect the nozzle, connection and clips when repeating several times which can lead to damage several machine elements (components). The second action is to use the unclogging pin tool at high temperature degree (say 265°C) to push the impurities as shown in Figure 12, which can affect the extruder base, the X-axis slider which is shown in Figure 1 and also the nozzle when repeating this cleaning several times. The third action is to use pure PLA materials to guarantee the fluidity of the melted composite material (wood fibers and PLA) in

Figure 10. Failure Case in a Pen Container Made of Pure PLA Material.

the next AM process.

3.2.2 Sliding Slot Disturbance Case

Figure 13 shows a sliding slot disturbance case. The printed part is also a bonbonniere like that illustrated in Figure 8. We have the same printing process inputs, except the total height. For the previous bonbonniere in Figure 8, it was 40mm, while it is here 50mm. The objective was to increase the height to avoid the previous defects. However, a failure occurred after a few millimeters of printing as shown in Figure 13. In this case, the extrusion of the melted material continued in a wrong way of localizing the successive layers on each other. Or the failure probably occurred due to a part clogging of nozzle (after the smooth flow time (T_F)) as shown in Figure 5. Small bits may enter the Y-Axis's slider and stay in contact between the BPF and the slider, which may lead to inaccuracy and wear problems (M.D.C.). In order to solve this problem, effective slicing algorithms can be used to provide an optimum connection between layers in this conical model with the objective of improving the surface quality[35].

3.2.3 Filament Tube Separation and Door Opening Case:

Figure 14 shows a filament tube separation and door opening case due to nozzle clogging which leads to several consequences. When comparing this case with the previous case in Subsection 3.1.4, it can be concluded that the continuity of the AM process may lead to multiple effects. Depending on the product complexity and printing time, it is possible to have more effects at several levels such as economy, safety, operation and environment.

4 DISCUSSION

In the different presented examples, we seek to provide logical and structured breakdown of AM deterioration mechanisms, addressing critical maintenance challenges. In addition, the integration of maintenance and uncertainty concepts enhances the different scientific foundations related to AM industrialization. According to several presented examples, we emphasize uncertainty as a

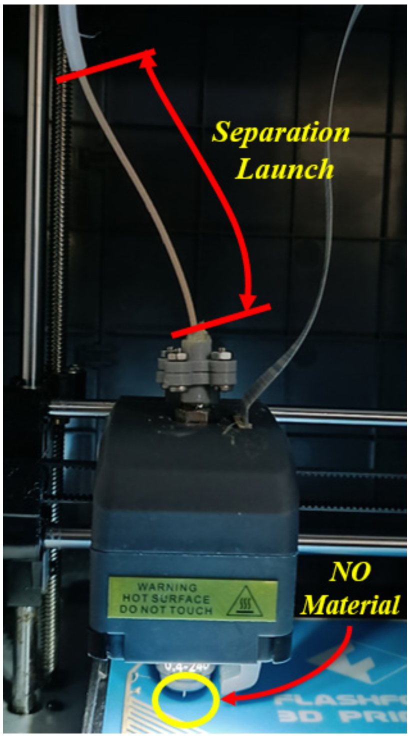


Figure 11. Damage Case of a Filament Tube Joint.

key industrialization barrier and maintenance as a key industrialization solution. Here, two machines belonging to Adventurer 3 series were used. For Figures 10 and 12, we used Adventurer 3 which is the previous version of Adventurer 3+ presented in Figure 1. There are small differences between the two versions such as the printer's touch screen (Mentoring Screen, see Figure 1). The different examples presented can be applicable to several FFF machines having the same printing strategies. In addition to the popularity of FFF technique, this study provides a roadmap to solve many issues and interpret several failure cases where the users are not able to understand the different failure causes. This also allows the user to become more familiar with this simple technique. The different findings and recommendations here can be arranged in logical ways to industrialize FFF technique. At least, it is possible to provide industry and academia with the best ways to popularize this technique. In addition, when reducing the defects, we improve the quality of additively manufactured products. Here, uncertainty studies play a vital role in allowing the user to repeat the same products several times without any deviation in their quality. Regarding the uncertainty aspect in this work, qualitative case studies, such as nozzle clogging and filament tube separation, effectively illustrate the deterioration concept, but quantitative data (e.g., failure rates, performance metrics) is needed to perform quantitative analysis for reproducibility objectives. Furthermore, when comparing the example presented in Figure 11 to that presented in Figure 14, we deduce the importance of a suitable monitoring system to reduce the different probable consequences. In this case, an advanced monitoring system is needed to avoid the occurrence of these issues[19,20]. When

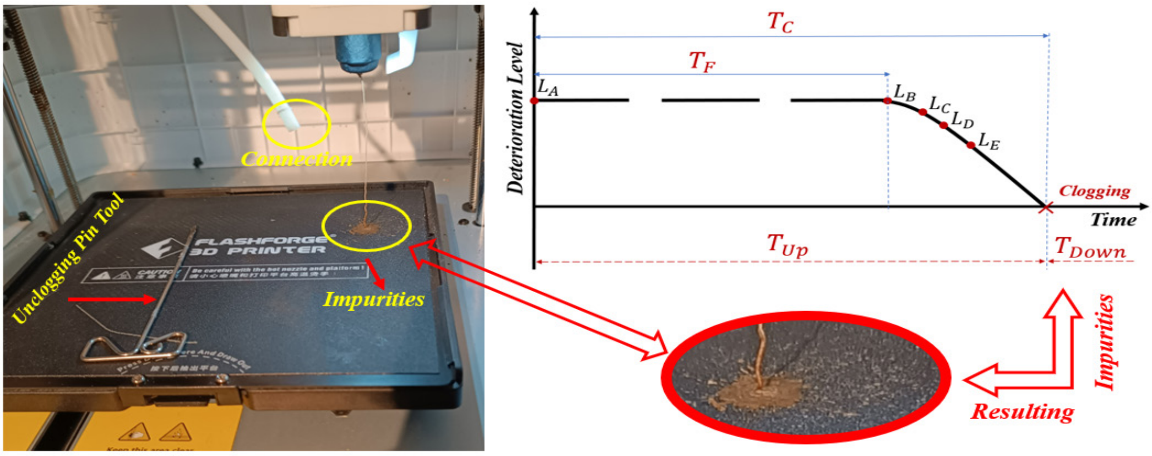


Figure 12. Total Nozzle Clogging Case with the Resulting Impurities.

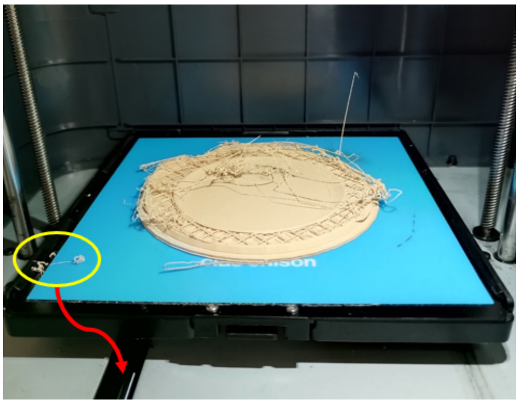


Figure 13. Sliding Slot Disturbance Case when Using Wood Fibers with PLA.

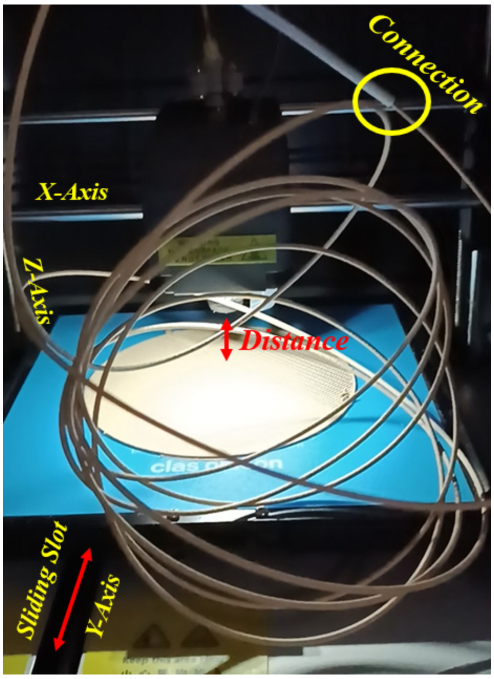


Figure 14. Filament Tube Separation and Door Opening Case.

integrating AI into conventional manufacturing processes, it is possible to control quality and optimize many processes. A special focus on AI-driven monitoring system enhances AM performance[27]. However, an economic point of view should be also considered when developing such monitoring systems. For example, in railway applications, it is important to use advanced monitoring systems which can be pretty expensive in order to avoid any probable catastrophes[36], however, in AM, we have to define the best compromise between the cost and the other requirements. So, other concepts such as optimization and reliability can be integrated in order to find the best compromise between cost and safety in AM technology. Furthermore, the integration of AI algorithms and Industrial Internet of Things (IIoT) offers a complete approach to enhancing AM processes. In conventional manufacturing, the IIoT serves as a crucial connector of devices and sensors to emphasize the importance of seamless data exchange for effective real-time quality monitoring and process optimization[37]. When integrating AI techniques into conventional manufacturing, we have several challenges and issues such as security risks, data management and so on[38]. The problem becomes much more complicated when dealing with AM technology. So, the current study presents the generalized "deterioration" concept, extending far beyond the concept of traditional failure analysis, which blazes a trail to develop effective strategies to overcome many challenges and issues in AM industrialization.

5 CONCLUSION

Several concepts such as defect, fault, failure and damage can affect the AM progress at several levels: AM process, design and resulting products (quality, usability …), even the machine elements and the surrounding environment. To identify the different levels of these concepts, functionalities were first treated by applying them to an AM machine. An AM machine (Adventurer 3+, manufactured by FLASHFORGE) was selected to define the different probable functions and their classifications. After that, a generalized concept called deterioration was defined to cover the different problem cases in AM technology. So, the deterioration assessment does not lead only to detect failure or damage cases, but to avoid any probable defects in the final products, which can highly improve the quality of the final products. In the future, it is the objective to use the current findings to apply FMEA and/or FMECA to discover the different potential risks regarding product, production and environment. In this way, we can use RCM to provide suitable action to maintain AM machines with the objective of increasing their reliability levels. In addition, during the next developments, several advanced AI techniques should take uncertainty issues into account. Furthermore, IIoT concept can be used to control the developed monitoring system in order to digitalize AM technology. To conclude, we must mention that although this study contributes to industrialization efforts concerning AM, several areas still need improvement, such as empirical validation, data-driven analysis, and extending discussions on AI and IIoT applications. Several studies should be carried out to improve empirical validity where quantitative data such as failure rates, degradation analysis, and performance metrics must be included to support the industrialization of FFF technique as a first step of IS4AM elaboration.

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Conflicts of Interest
The author declared no conflict of interest.

Data Availability
All data generated or analyzed during this study are included in this published article.

Author Contribution
Ghais Kharmanda studied, wrote, reviewed, and corrected this article.

Abbreviation List
AI, Artificial intelligence
AM, Additive manufacturing
FFF, Fused filament fabrication
FMECA, Failure modes, effect and criticality analysis
IS4AM, Industrialization standard for AM
M.D.C., Multiple deterioration category
PLA, Polylactic acid
RCM, Reliability-centered maintenance
S.D.C., Single deterioration category
TPM, Total productive maintenance

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