Enhancing Resilience in 3D Printing Operations: A FRAM-based Analysis of Maintenance System Variability

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Abstract. Additive manufacturing processes offer significant flexibility advantages due to the ability to produce without the requirement for costly tooling [1]. Due to its low acquisition cost, one of the most widely adopted technologies is FDM (Fused Deposition Modeling), utilized extensively in the realm of 3D Printing (I3D) [1]. Such printers, consolidated within a singular location to enhance productivity rates, are commonly referred to as I3D printer farms [2]. Within this operational framework, the integration of maintenance management with operational oversight presents a paramount challenge in ensuring machine availability for uninterrupted printing [3].

In light of this, a case study was undertaken to address the inquiry: "How can resilience be enhanced within a 3D printing farm through machine maintenance?". To this end, the Resilience Engineering approach was selected to capture the system resonances inherent in 3D printing, employing the Functional Resonance Analysis Method (FRAM) as developed by Erik Hollnagel [4]. This methodology was applied within the Open Laboratory of Brasília (LAB) at the Faculty of Technology, University of Brasília, housing a 3D printer farm consisting of 35 operational machines servicing the community.

The research methodology encompassed a literature review within the Scopus database, yielding 22 scientific articles relating FRAM to Maintenance. Predominantly, these applications were observed within Engineering (21.4%) and Computer Science (11.5%). Notably, no literature was found proposing the application of FRAM within the context of I3D maintenance.

Subsequently, semi-structured interviews were conducted with three LAB members to delineate and comprehend internal processes within the laboratory. These interviews revealed two principal maintenance-related issues: a) a substantial turnover within the team over the past two years, resulting in significant knowledge loss; and b) after four years of utilization, a decline in machine reliability, consequentially escalating failure rates.

As in FRAM, the system is described as a set of functions that interact with each other through what are called variabilities (conditions or circumstances that influence how the function is performed in different contexts) [4], the model was created using the FRAM Model Visualizer software, which allows for the inclusion of the variables Input, Output, Precondition, Resource, Control, and Time. The final version, resulting from iterative reviews that included expert FRAM consultations, is presented in Fig. 1. The functions highlighted in red represent those related to knowledge management and data input into the system. The functions in gray depict the resources available for carrying out maintenance. In blue, we have the functions for testing and releasing the machine for use, and finally, in yellow, the functions directly related to task execution.

With the system modeled, it is possible to analyze resonances, that is, identify emerging patterns of system behavior. As Fig. 1 shows, all functions exhibit some variability, represented by the curves behind the function name. The importance here is to better understand the system dynamics in order to identify not only the direct causes of failures, but also the resonances that contribute to the overall performance of the system in different operational conditions and contexts [4]. During system modeling, four critical resonance points affecting maintenance system effectiveness were identified: **A) Team Training:** The current knowledge management strategy predominantly emphasizes manual task execution, without adequate incorporation of Standard Operating Procedures (SOPs). This approach has resulted in the dissipation of accumulated knowledge from prior teams, thereby compromising efficiency and knowledge transmission; **B) Access and Utilization of Standard Operating Procedures (SOPs):** SOPs play a pivotal role in guiding standardized and efficient maintenance activities. However, current accessibility for consultation by the team was found to be lacking; **C) Inventory Management and Spare Part Availability:** Effective component replacement and prevention of part cannibalization between printers hinge upon meticulous inventory control and spare parts management. Regrettably, there is a dearth of an organized system for recording available parts and exchanges made, alongside reports of inter-machine part exchanges; **D) Maintenance Recordkeeping and Traceability:** Systematic maintenance recording is essential for fault traceability and monitoring maintenance system performance indicators. However, extant records lack structure and are often absent, thereby compromising data reliability and impeding effective maintenance history analysis.

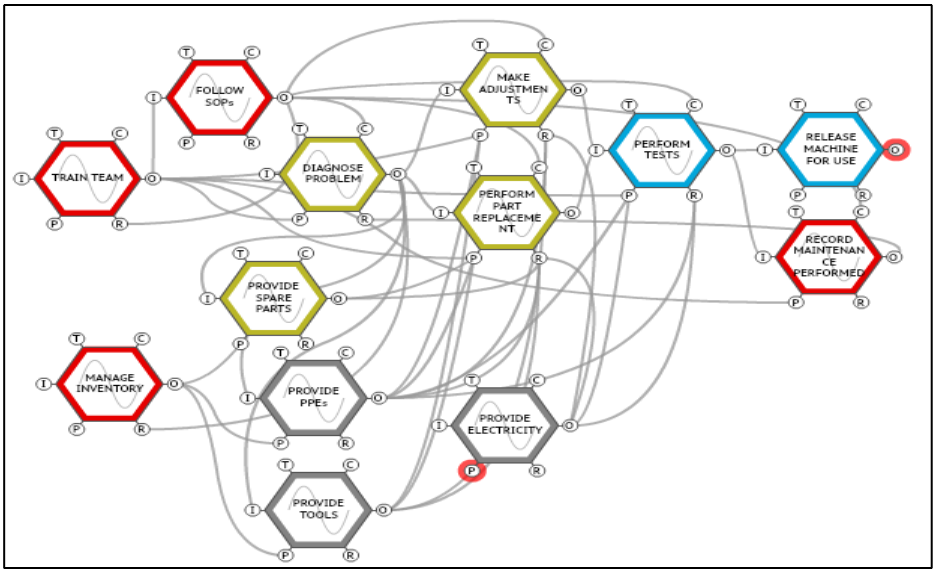

Fig. 1: LAB Maintenance system model. Authors, 2023

Finally, given the recognized importance of continuous learning capacity in system resilience [5], the following measures were proposed: **A) Restructuring of Maintenance Training:** Incorporate a comprehensive review of primary failure causes and maintenance activities, encompassing both preventive and corrective measures. This should be complemented by the inclusion of additional procedures related to the maintenance system, such as consultation of maintenance history utilizing SOPs as a reference; **B) Review and Update of SOPs:** Conduct a thorough review of SOPs associated with the maintenance system, ensuring their ready availability to the team. Former laboratory members could be invited to contribute to this review process, leveraging their accumulated knowledge. **C) Development and Implementation of a Spare Parts Inventory Control Spreadsheet:** This spreadsheet should include specific fields for recording part exchanges and establish a predictive system for spare parts requirements, informed by inventory history and exchange demands; **D) Restructuring of Maintenance Record Spreadsheet and Development of a Specific SOP for Recording:** The objective is to enhance the accessibility and user-friendliness of the spreadsheet, alongside developing an SOP dedicated to the maintenance recording process, aimed at augmenting the accuracy and reliability of recorded data.

It is imperative to underscore that continual monitoring and reinforcement within the LAB's daily operations are pivotal in ensuring the efficacy of proposed measures. Subsequently, through these actions, the monitoring of enhanced system capacity is proposed, facilitated by indicators such as average printer failure rate, average time between maintenance interventions on the same printer, average machine downtime during preventive and corrective maintenance, and average machine downtime due to spare part unavailability. The data required to track the proposed indicators will be provided by the LAB team through the Maintenance Record Spreadsheet.

Keywords: Additive Manufacturing, Maintenance, FRAM, Resilience Engineering.

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