Online Appendix of: “Integrating additive manufacturing repair into age-based preventive maintenance policies”

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Online Appendix

In this online appendix, we report the literature review, figures illustrating the maintenance policy configurations, and the references of the paper entitled “Integrating Additive Manufacturing Repair into Age-Based Preventive Maintenance Policies”, presented at the Twenty-Fourth International Working Seminar on Production Economics, University of Innsbruck, SOWI Building, Universitaetsstrasse 15, A-6020 Innsbruck, 24–27 February 2026. Specifically, Appendix A reports the literature review, Appendix B presents the figures illustrating the maintenance policy configurations, and Appendix C contains the references of the paper.

Appendix A

Literature Review

Maintenance planning and spare parts inventory management have long been interdependent research domains, particularly because equipment failures immediately translate into spare parts demand (Durugbo, 2020). Classical studies traditionally treat maintenance planning and spare parts management as separate problems, but their integration has gained growing attention due to the strong coupling between failure behaviour, part availability, and operational downtime (Scarf et al., 2024). Early research on maintenance planning focused on preventive strategies such as age-based or condition-based policies (Barlow & Hunter, 1960; H. Wang, 2002), and subsequent studies refined age-based models by introducing failure thresholds, minimal repair rules, and downtime-related constraints (Nakagawa, 1981, 1982). Parallel to this, joint optimization models began to incorporate the interplay between maintenance planning and spare parts management. Foundational work demonstrated the benefits of simultaneously optimizing maintenance planning and parts management rather than treating them sequentially (Kabir & Al-Olayan, 1996). Later contributions expanded these models to include multi-component systems, opportunistic replacement, and forecasting-driven replenishment (Nguyen et al., 2017; Zhu et al., 2020). Reviews by Van Horenbeek et al. (2013) Van Horenbeek et al., (2013) and Zahedi-Hosseini et al., (2017) further highlighted the growing relevance of integrated maintenance–inventory approaches.

In recent years, the emergence of Additive Manufacturing (AM) has introduced new opportunities for spare parts inventory management, motivating a large and diverse research stream on AM-enabled supply chains (Cantini et al., 2024). Most of this literature has examined AM as a second sourcing option for producing new parts, typically on-demand and with reduced or negligible lead times build upon the dual sourcing paradigm (Minner, 2003) evaluating when it is optimal to use Conventional Manufacturing (CM) or AM for spare parts management. For example, Liu et al., (2014) and Song & Zhang, (2016) demonstrate that on-demand AM can reduce safety stock and inventory costs, though both works overlook the different reliability often associated with printed components. Subsequent contributions incorporate more realistic AM characteristics. Gabor & Sleptchenko, (2018) and Cestana et al., (2019) model uncertain yield or setup-time differences while Knofius et al., (2021) for the first time explicitly include reliability differences between CM and AM parts using a Markov decision process. Exploiting similar Markov decision processes Westerweel et al., (2021) show that internally printed AM parts can improve availability despite their reliability penalty. Sgarbossa et al., (2021) further examine how AM technologies and post-processing treatments affect inventory decisions through their influence on part reliability. Following their approach Cantini et al., (2025) investigated how qualifications cost affects the sourcing decision between AM and CM while Lolli et al., (2024) evaluated the impact of stocks constraint on the effectiveness of insourcing a 3D printer. For a full review on the theme the reader can refer to recent works (Alzahmi et al., 2025; Coruzzolo et al., 2022).

The previously cited works mainly address spare parts inventory management and do not explicitly integrate maintenance optimization into the decision-making process. In fact, to date, only a very limited number of studies directly incorporate Additive Manufacturing (AM) into preventive maintenance policy optimization. To the best of our knowledge, only Westerweel et al., (2019) and Lolli et al., (2022) explicitly embed AM within age-based preventive maintenance models.

Specifically, Westerweel et al. (2019) were the first to evaluate the impact of AM on preventive maintenance by adapting Nakagawa's classical age-based maintenance models (Nakagawa, 1981). In their framework, AM is considered a feasible on-demand option for replacing a failed component. The model optimizes a failure-time threshold: if failure occurs before this threshold, a part is printed on demand using AM and maintenance actions are then scheduled on the printed component; conversely, if failure occurs after the threshold, the system remains in a state of downtime until the end of the maintenance cycle. A key novelty of their approach, compared to Nakagawa (1981), is that age-based preventive maintenance is also performed on the AM-produced "emergency" part, rather than discarding it upon the arrival of a conventionally manufactured replacement, acknowledging that the printed component may still have residual useful life.

Building on this framework, Lolli et al. (2022) extended the models of Westerweel et al. (2019) by relaxing the assumption that no failures can occur during the replenishment lead time of conventionally manufactured parts. This extension was applied to all the models proposed by Westerweel et al. (2019), including those featuring only conventionally manufactured (CM) parts, as they demonstrated that, under long lead times, the no-failure assumption becomes unrealistic. In addition, Lolli et al. (2022) proposed a more general preventive maintenance model that incorporates not one but two alternative AM printing options and validated it using a large-scale dataset derived from Sgarbossa et al. (2021). Their results demonstrate that AM can significantly reduce downtime and increase system flexibility when employed as an emergency replacement source; however, they also show that the high cost of fully AM-produced parts substantially limits their economic attractiveness, in line with industrial evidence.

However, both of these papers do not consider the most recent technological developments in AM that enable repair rather than full part replacement (Wang et al., 2023).At present, the literature on AM-based repair primarily addresses this topic from a technological perspective, focusing on technological feasibility, process capability, and the mechanical properties of repaired components as shown in a recent review (Kanishka & Acherjee, 2023) but it does not investigate repair from a maintenance optimization perspective. This creates a gap that is not merely theoretical but also highly practical. As discussed in the introduction, AM-based repair solutions are already being adopted by several industrial companies in real maintenance contexts (Baker Hughes, 2025; Peter Zelinski, 2025; Siemens Energy, 2025); however, in the absence of formal models and decision-support frameworks, managers are effectively left to rely on ad hoc judgments when making maintenance decisions. The present work aims to close this gap by explicitly integrating AM-enabled repair into preventive maintenance optimization.

More specifically, we focus on age-based preventive maintenance settings, in which the value of repair can be particularly significant. In such settings, failures occurring before scheduled replacements may force the system into prolonged downtime due to spare part unavailability or long replenishment lead times. By contrast, AM-based repair, characterized by reduced lead times and higher responsiveness, can substantially mitigate these negative effects, thereby improving system availability and supporting more resilient maintenance strategies.

Building on the limited body of literature that integrates Additive Manufacturing (AM) into preventive maintenance, we propose two novel models that capture alternative ways of incorporating AM-based repair into maintenance decision-making. Specifically, we consider: (i) a policy in which repair is employed exclusively as an emergency solution to avoid backorders during the replenishment lead time of replacement parts; and (ii) a policy in which repair serves as a substitute for stocking conventionally manufactured (CM) components. These two proposed policies are benchmarked against two reference policies from the literature (Lolli et al., 2022): a CM-based policy, where only conventionally manufactured parts are used for both preventive and corrective maintenance actions; and an AM-replacement policy, in which fully AM-produced parts are manufactured on demand following a failure. By analytically comparing these policies, we identify the operational conditions under which AM repair becomes advantageous and show that repair can unlock benefits not achievable through replacement-only AM approaches.

Appendix B

Figures of Section 3. Maintenance Models

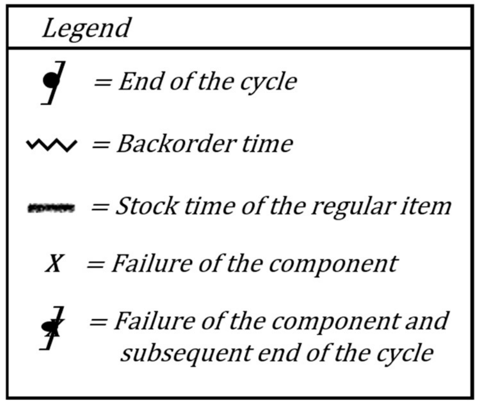


Figure B1: Legend.

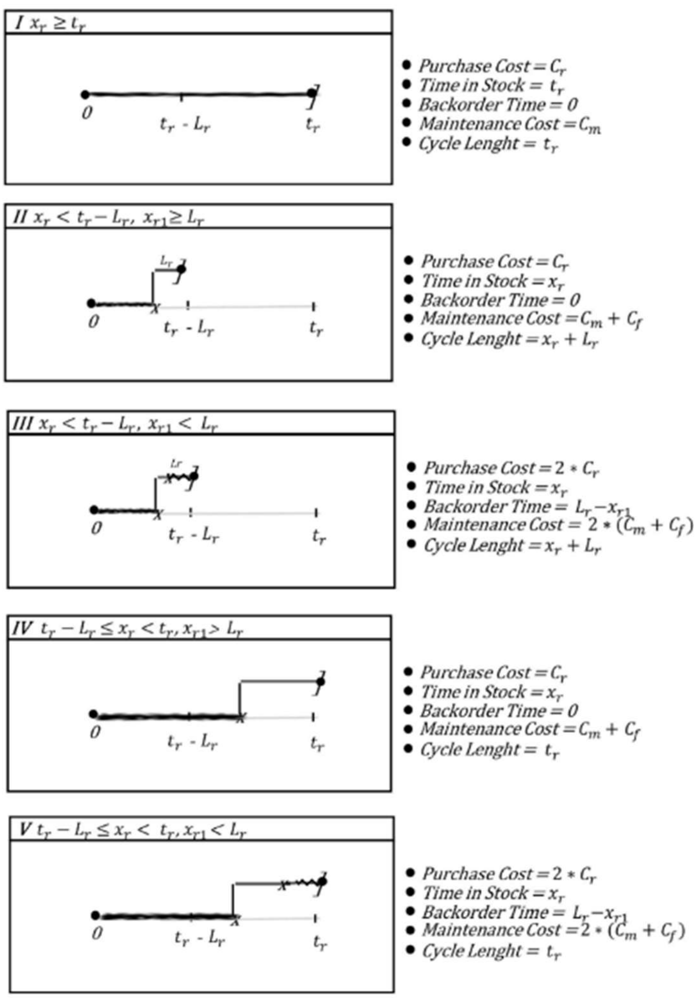
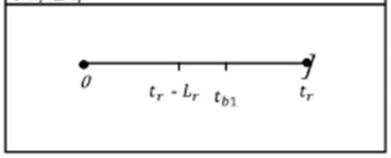


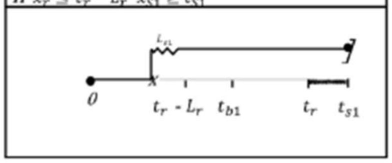
Figure B2: Possible configurations for R’ from Lolli et al., (2022).

I $x_r \geq t_r$



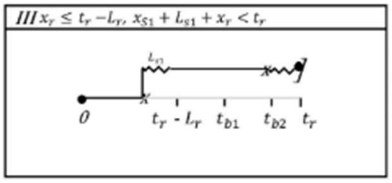
- *Purchase Cost* = C_r
- *Time in Stock = 0*
- *Backorder Time = 0*
- *Maintenance Cost*= C_m
- *Cycle Lenght*= t_r

II $x_r \leq t_r - L_r$ $x_{S1} \geq t_{S1}$



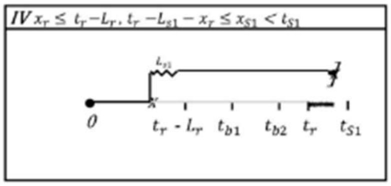
- *Purchase Cost* = $C_r + C_{S1}$
- *Time in Stock* = $t_{s1} + L_{s1} + x_r - t_r$
- *Backorder Time* = L_{s1}
- *Maintenance Cost* = $2 * C_m + C_f$
- *Cycle Lenght* = $t_{s1} + L_{s1} + x_r$

III $x_r \leq t_r - L_r$, $x_{S1} + L_{s1} + x_r < t_r$



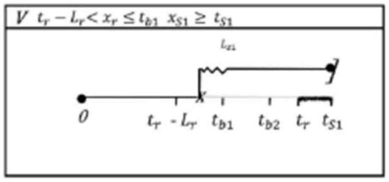
- *Purchase Cost* = $C_r + C_{S1}$
- *Time in Stock = 0*
- *Backorder Time* = $L_{S1} + t_r - (x_{S1} + L_{S1} + x_r)$
- *Maintenance Cost* = C_m
- *Cycle Lenght*= t_r

IV $x_r \leq t_r - L_r$, $t_r - L_{s1} - x_r \leq x_{S1} < t_{S1}$



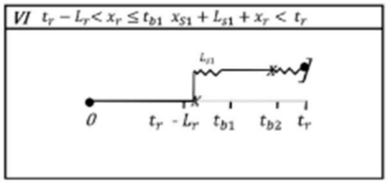
- *Purchase Cost* = $C_r + C_{S1}$
- *Time in Stock* = $x_{s1} + L_{s1} + x_r - t_r$
- *Backorder Time* = L_{s1}
- *Maintenance Cost* = $2 * C_m + C_f$
- *Cycle Lenght* = $x_{s1} + L_{s1} + x_r$

V $t_r - L_r < x_r \leq t_{b1}$ $x_{S1} \geq t_{S1}$



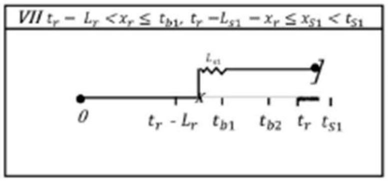
- *Purchase Cost* = $C_r + C_{S1}$
- *Time in Stock* = $t_{S1} + L_{s1} + x_r - t_r$
- *Backorder Time* = L_{s1}
- *Maintenance Cost* = $C_f + 2 * C_m$
- *Cycle Lenght* = $x_r + L_{s1} + x_{S1}$

VI $t_r - L_r < x_r \leq t_{b1}$ $x_{S1} + L_{s1} + x_r < t_r$



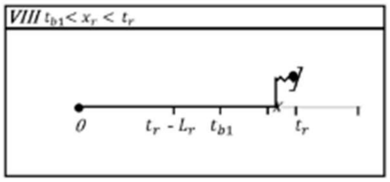
- *Purchase Cost* = $C_r + C_{S1}$
- *Time in Stock = 0*
- *Backorder Time* = $L_{s1} + t_r - (x_r + L_{s1} + x_{S1})$
- *Maintenance Cost* = $2 * (C_m + C_f)$
- *Cycle Lenght* = t_r

VII $t_r - L_r < x_r \leq t_{b1}$, $t_r - L_{s1} - x_r \leq x_{S1} < t_{S1}$



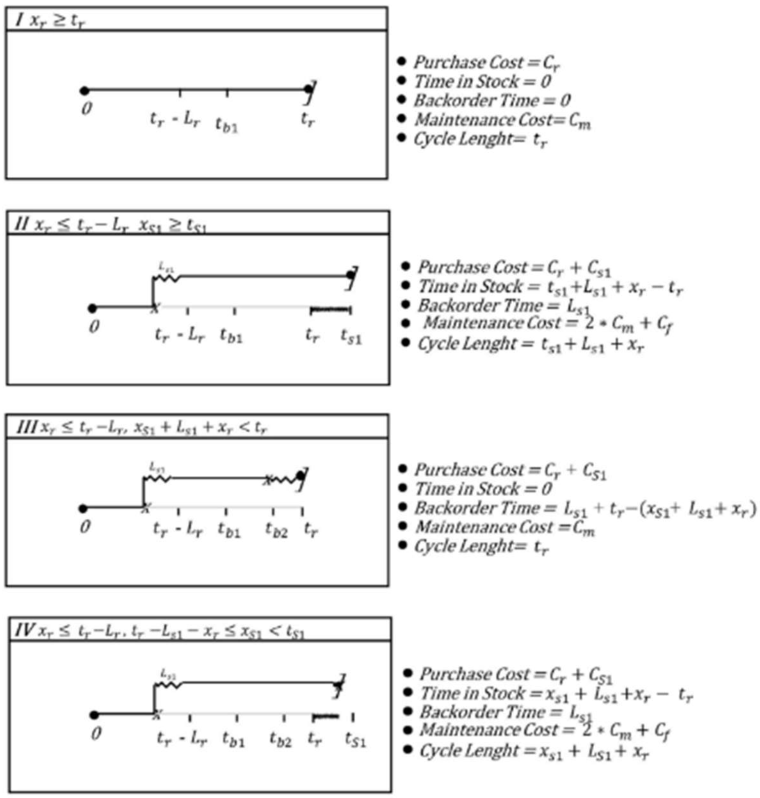
- *Purchase Cost* = $C_r + C_{S1}$
- *Time in Stock* = $x_{S1} + L_{s1} + x_r - t_r$
- *Backorder Time* = L_{s1}
- *Maintenance Cost* = $(C_m + C_f) * 2$
- *Cycle Lenght* = $x_r + L_{s1} + x_{S1}$

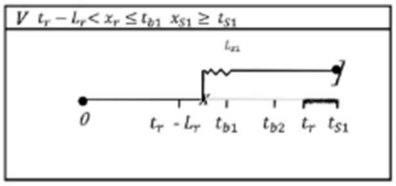
VIII $t_{b1} < x_r < t_r$



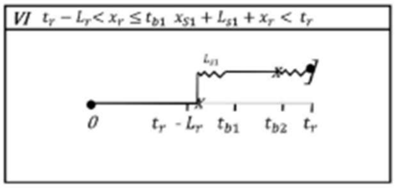
- *Purchase Cost* = C_r
- *Time in Stock = 0*
- *Backorder Time* = $t_r - x_r$
- *Maintenance Cost* = $C_m + C_f$
- *Cycle Lenght* = t_r

Figure B3: Possible configurations for L from Lolli et al., (2022).

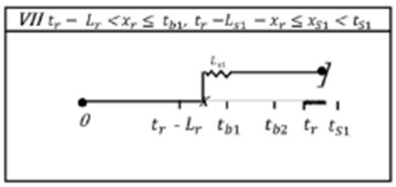




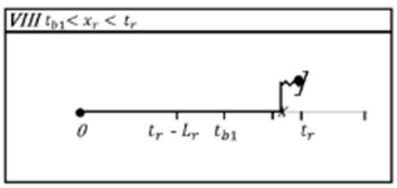
- *Purchase Cost* $= C_r + C_{S1}$
- *Time in Stock* $= t_{S1} + L_{s1} + x_r - t_r$
- *Backorder Time* $= L_{s1}$
- *Maintenance Cost* $= C_f + 2 * C_m$
- *Cycle Lenght* $= x_r + L_{s1} + x_{S1}$



- *Purchase Cost* $= C_r + C_{S1}$
- *Time in Stock* $= 0$
- *Backorder Time* $= L_{s1} + t_r - (x_r + L_{s1} + x_{S1})$
- *Maintenance Cost* $= 2 * (C_m + C_f)$
- *Cycle Lenght* $= t_r$

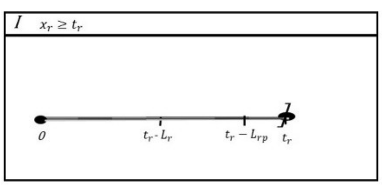


- *Purchase Cost* $= C_r + C_{S1}$
- *Time in Stock* $= x_{S1} + L_{s1} + x_r - t_r$
- *Backorder Time* $= L_{s1}$
- *Maintenance Cost* $= (C_m + C_f) * 2$
- *Cycle Lenght* $= x_r + L_{s1} + x_{S1}$

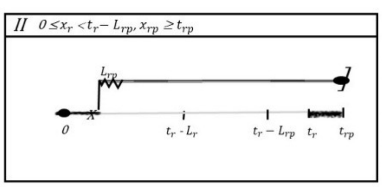


- *Purchase Cost* $= C_r$
- *Time in Stock* $= 0$
- *Backorder Time* $= t_r - x_r$
- *Maintenance Cost* $= C_m + C_f$
- *Cycle Lenght* $= t_r$

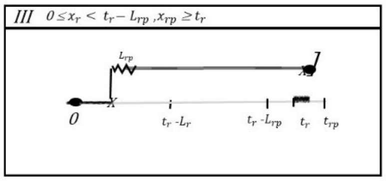
Figure B4: Possible configurations for G.



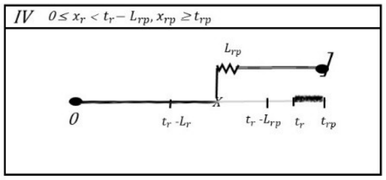
- *Purchase Cost* $= C_r$
- *Time in Stock* $= 0$
- *Backorder Time* $= 0$
- *Maintenance Cost* $= C_m$
- *Cycle Lenght* $= t_r$
- *Repair Cost* $= 0$



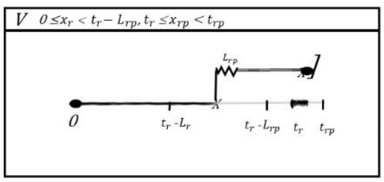
- *Purchase Cost* $= C_r$
- *Time in Stock* $= t_{rp} + x_r + L_{rp} - t_r$
- *Backorder Time* $= L_{rp}$
- *Maintenance Cost* $= 2 * C_m + C_f$
- *Cycle Lenght* $= x_{rp} + L_{rp} + x_r$
- *Repair Cost* $= C_{rp}$



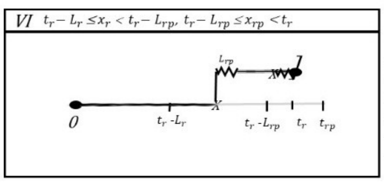
- *Purchase Cost* = C_r
- *Time in Stock* = $x_r + L_{rp} + x_{rp} - t_r$
- *Backorder Time* = L_{rp}
- *Maintenance Cost*= $2^* C_m + 2^* C_f$
- *Cycle Lenght*= $x_r + L_{rp} + x_{rp}$
- *Repair Cost*= C_{rp}



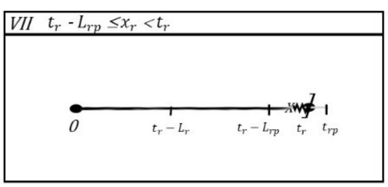
- *Purchase Cost* = C_r
- *Time in Stock* = $t_{rp} + L_{rp} + x_r - t_r$
- *Backorder Time* = L_{rp}
- *Maintenance Cost*= $2^* C_m + C_f$
- *Cycle Lenght*= $x_r + L_{rp} + x_{rp}$
- *Repair Cost*= C_{rp}



- *Purchase Cost* = C_r
- *Time in Stock* = $x_{rp} + L_{rp} + x_r - t_r$
- *Backorder Time* = L_{rp}
- *Maintenance Cost*= $2^* C_m + 2^* C_f$
- *Cycle Lenght*= $x_r + L_{rp} + x_{rp}$
- *Repair Cost*= C_{rp}



- *Purchase Cost* = C_r
- *Time in Stock* = 0
- *Backorder Time* = $(L_{rp} + t_r) - x_r + L_{rp} + x_{rp})$
- *Maintenance Cost*= $2^* C_m + 2^* C_f$
- *Cycle Lenght*= t_r
- *Repair Cost*= C_{rp}



- *Purchase Cost* = C_r
- *Time in Stock* = 0
- *Backorder Time* = $t_r - x_r$
- *Maintenance Cost*= $C_m + C_f$
- *Cycle Lenght*= t_r
- *Repair Cost*=0

Figure B5: Possible configurations for H.

Appendix C

List of References

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