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A Process-Based Cost Estimation Model for Metal Spare Parts Production Using Additive Manufacturing

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Abstract

Despite its potential to revolutionize spare parts production, the widespread adoption of Metal Additive Manufacturing (MAM) remains limited, primarily due to the lack of comprehensive cost estimation models that fully capture the intricacies of the manufacturing process chain. This study develops a process-based cost estimation model that systematically evaluates design, material, manufacturing, post-processing, and qualification costs through detailed process mapping and cost allocation. The process-based analysis demonstrates that manufacturing costs constitute the largest portion of total costs across all components, with sintering costs remaining constant regardless of component size. Post-processing costs exhibit substantial variation based on component complexity, while qualification costs reflect application-specific requirements. The developed model provides quantitative insights for supply chain managers in optimizing spare parts production strategies and resource allocation. This study advances the understanding of MAM economics and offers practical implications for organizations seeking to integrate additive manufacturing in their spare parts supply chain operations.

Keywords
Spare Parts Management, Supply Chains, Metal Additive Manufacturing, Cost Estimation Model, Bound Metal Deposition.

1. Introduction
The growing adoption of Additive Manufacturing (AM) has transformed traditional production paradigms by enabling the efficient fabrication of complex, customized components on demand. Among its various applications, AM plays a pivotal role in the production of spare parts, addressing critical challenges such as inventory management (Togwe et al., 2019), lead time reduction (Akmal et al., 2022), reduced material wastage (Debnath et al., 2022) and the risks associated with part obsolescence (Attaran, 2017). However, the broader integration of AM into spare parts supply chains is contingent upon a detailed understanding of its cost implications. Accurate cost estimation models are essential for assessing the economic viability of AM technologies, facilitating informed decision-making for stakeholders across design, manufacturing, and supply chain operations (Mecheter et al., 2022).

The need for metal spare parts in industries such as aerospace, automotive, and machinery is critical for maintaining operational efficiency and reducing downtime, especially when traditional manufacturing methods are either too costly or no longer feasible due to discontinued production lines. Within the spectrum of AM processes, Metal Additive Manufacturing (MAM) has emerged as a transformative technology, enabling the production of complex geometries with minimal material waste. Unlike traditional metal AM processes like Selective Laser Sintering (SLS) and Electron Beam Melting (EBM), Bound Metal Deposition (BMD) is an extrusion-based process that uses metal powder bound with a polymer binder. After printing, the binder is removed through a solvent or through thermal debinding, and then part is sintered to achieve the final density (Iacopo et al., 2022). This combination of process steps enables the production of dense, robust metal parts while mitigating some of the challenges related to material handling and operational complexity in other metal AM methods. The economic feasibility of BMD, particularly for spare parts production, remains underexplored, with cost estimation models for this specific technology still in their infancy (Figure 1).

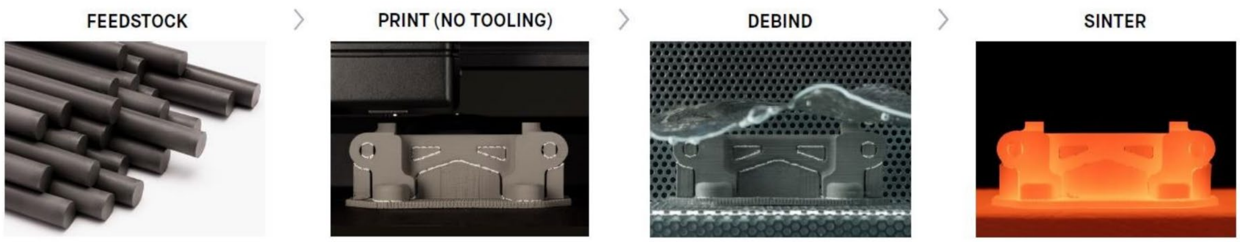

Figure 1. General Flow of BMD process (Sartini et al., 2024)

This study focuses on developing a comprehensive cost estimation model tailored to BMD technology for the production of metal spare parts. The model incorporates key parameters such as material usage, process times, energy usage, post- processing requirements, and quality assurance costs to provide a detailed breakdown of production expenses. By focusing on case studies involving distinct spare parts, the research highlights the cost structures associated with BMD processes and identifies opportunities for cost optimization.

2. Relevant Literature

AM cost estimation models have been developed across productivity, feasibility, and supply chain implications. Salmi et al. (2020) developed a cost estimation model mainly related to medical spare parts during the COVID-19 pandemic, including basic manufacturing parameters such as machinery, maintenance, raw materials, labor, overhead, and sterilization costs. Ivan & Yin (2017), analyzed the viability of local AM production for spare parts in the automotive industry based on dealer price, inventory carrying costs, and basic production costs. Similarly, Ahlsell et al. (2022), evaluated the profitability of the switch from traditional to AM production based on holistic supply chain costs. However, none of the two works took into account critical factors such as design optimization and qualification costs.

Cardeal et al. (2021) proposed a process-based cost model taking into account design considerations; however, they simplified the post-processing requirements and failed to consider qualification standards in their approach. H. Khajavi et al. (2018) analyzed supply chain configurations; however, since the work focused mainly on the aerospace applications of additive manufacturing, it lacked in-depth part-specific analysis. Kozin et al. (2022) developed a cost estimation model to explore the economic feasibility of producing rubber and plastic spare parts for special vehicles in the oil and gas industry. The cost estimation model compared traditional procurement with in-house AM production, considering only the production costs including equipment, materials, and operating costs.

Isasi-Sanchez et al. (2020) proposed a cost estimation by considering volume, density, and complexity factors, although their model did not cater to the specific characteristics of the processes. Sartini et al. (2024) developed an analytical cost model for the BMD process, however it does not account for the redesign costs or the design optimization costs, and the part qualification costs involved in the case of spare parts production and commissioning.Current models fail to integrate design, material, manufacturing, post-processing, and qualification costs comprehensively into one framework.

Table 1. Comparative Analysis of Cost Structures in AM Spare Parts Literature.

Reference	Design Costs	Material Costs	Manufacturing Costs	Post-Processing Costs	Part Qualification Costs	BMD Technology
(Salmi et al., 2020)	✗	✓	✓	✗	✗	✗
(Ivan & Yin, 2017)	✗	✓	✓	✗	✗	✗
(Cardeal et al., 2021)	✓	✓	✓	✓	✗	✗
(H. Khajavi et al., 2018)	✗	✓	✓	✗	✗	✗
(Ahlsell et al., 2022)	✗	✓	✓	✓	✗	✗
(Kozin et al., 2022)	✗	✓	✓	✗	✗	✗
(Isasi-Sanchez et al., 2020)	✗	✓	✓	✓	✗	✗
(Sartini et al., 2024)	✗	✓	✓	✓	✗	✓
This Study	✓	✓	✓	✓	✓	✓

This comparative analysis in Table 1 highlights the literature gap, wherein all the previous cost estimation models of additive manufacturing for spare parts supply chains considered only selective cost components. In this respect, the proposed model provides a holistic framework that includes all the critical cost elements including domains of BMD technology specifications, design/redesign costs involved, post-processing requirements, and part qualification protocols.

3. Methodology

This section develops the systematic approach toward the development of a process-based cost estimation model for the additive manufacture of spare parts by BMD technology.

3.1. Cost Estimation Model

C_{Total} calculates the total cost of producing an AM spare part using the BMD methodology. It represents the sum of all the major cost components, including part design, AM raw material, manufacturing, post-processing, and part qualification costs.

$$C_{Total} = C_{Design} + C_{AM\ Material} + C_{Manufacturing(BMD)} + C_{Post\ Processing} + C_{Part\ Qualification} \quad (1)$$

3.1.1. Spare Part Design Cost

The design cost C_{Design} is the total cost of using a 3D scanner, design software, and designer labor to create the spare part's design.

$$C_{Design} = \left(C_{3D\ Scanner} + C_{Design\ Software} + C_{Designer}\right) \quad (2)$$

$$C_{Design} = \left(\frac{C_{Scanner\ Initial}}{H_{Annual\ Usage}} \times T_{Scan}\right) + \left(\frac{C_{Software\ License}}{N_{Parts}}\right) + \left(T_{Design} \times R_{Designer}\right) \quad (3)$$

Whereas $C_{\text{Scanner Initial}}$ is the initial cost of the 3D scanner, $H_{\text{Annual Usage}}$ represents the annual usage hours of the 3D scanner, T_{Scan} denotes the scanning time, $C_{Software\ License}$ is the cost of the design software license, N_{Parts} is the number of parts produced, T_{Design} indicates the design time, and $R_{Designer}$ is the hourly rate for design labor.

3.1.2. AM Material Cost

$$C_{\text{AM Material}} = (C_{\text{Metal Rods}} + C_{\text{Ceramic Material}}) \quad (4)$$

$$C_{\text{AM-Material}} = (W_{\text{Metal Rods}} \times P_{\text{Metal Rods}}) + (W_{\text{Ceramic Rods}} \times P_{\text{Ceramic Rods}}) \quad (5)$$

Whereas $W_{\text{Metal Rods}}$ is the weight of metal rods required for the printing phase of BMD for a specific spare part, $P_{\text{Metal Rods}}$ represents the cost per unit weight of the metal rods, $W_{\text{Ceramic Rods}}$ is the weight of the ceramic material required for the printing phase of BMD for a specific spare part, and $P_{\text{Ceramic Rods}}$ is the cost per unit weight of the ceramic rods.

3.1.3. Spare Part Manufacturing Cost (Bound Metal Deposition)

$$C_{\text{Manufacturing (BMD)}} = \left(C_{\text{Printing}} + C_{\text{Debinding}} + C_{\text{Sintering}}\right) \tag{6}$$

- **Printing Cost**

$$C_{\text{Printing}} = C_{\text{Operator}} + C_{\text{AM Machine Depreciation}} + C_{\text{AM Machine Maintenance}} + C_{\text{Energy Usage}} \tag{7}$$

$$\begin{aligned} C_{\text{Printing}} = &\left(R_{\text{Printer Operator}} \times P_{Setup\ Time}\right) + \left(D_{\text{Printer}} \times T_{\text{Printing}}\right) \\ &+\left(M_{\text{Printer}} \times T_{\text{Printing}}\right) + \left(P_{\text{Electricity}} \times \left(E_{\text{Printer}} \times T_{\text{Printing}}\right)\right) \end{aligned} \tag{8}$$

Whereas $R_{Operator}$ is the hourly rate of the operator, $P_{Setup\ Time}$ is the time required to setup the printer and load STL files to the printer, $T_{Printing}$ represents the printing time, $D_{Printer}$ denotes the printer's depreciation per hour, $M_{Printer}$ accounts for printer maintenance costs, $E_{Printer}$ specifies the printer's energy usage rate and $P_{Electricity}$ is the cost of electricity per unit.

- **Debinding Costs**

$$C_{\text{Debinding}} = C_{\text{Machine Depreciation}} + C_{\text{Machine Maintenance}} + C_{\text{Energy Usage}} \tag{9}$$

$$C_{\text{Debinding}} = \left(D_{\text{Furnace}} \times T_{\text{Debinding}}\right) + \left(M_{\text{Furnace}} \times T_{\text{Debinding}}\right) + \left(P_{\text{Electricity}} \times \left(E_{\text{Debinding}} \times T_{\text{Debinding}}\right)\right) \tag{10}$$

Whereas $T_{Debinding}$ represents the Debinding time, $D_{Furnace}$ denotes the furnace depreciation per hour, $M_{Furnace}$ accounts for furnace maintenance costs, $E_{Debinding}$ specifies the furnace energy usage rate and $P_{Electricity}$ is the cost of electricity per unit.

- **Sintering Costs**

$$C_{\text{Sintering}} = C_{\text{AM Machine Depreciation}} + C_{\text{AM Machine Maintenance}} + C_{\text{Energy Usage}} \tag{11}$$

$$C_{\text{Sintering}} = \left(D_{\text{Furnace}} \times T_{\text{Sintering}}\right) + \left(M_{\text{Furnace}} \times T_{\text{Sintering}}\right) + \left(P_{\text{Electricity}} \times \left(E_{\text{Sintering}} \times T_{\text{Sintering}}\right)\right) \tag{12}$$

Whereas $T_{Sintering}$ represents the sintering time, $D_{Furnace}$ denotes the furnace depreciation per hour, $M_{Furnace}$ accounts for furnace maintenance costs, $E_{Sintering}$ specifies the furnace energy usage rate and $P_{Electricity}$ is the cost of electricity per unit.

3.1.5. Post-processing costs

$$C_{\text{Post Processing}} = C_{\text{Heat Treatment}} + C_{\text{Machining}} + C_{\text{Surface Finishing}} \tag{13}$$

- **Machining Costs**

$$C_{\text{Machining}} = C_{\text{Labor}} + C_{\text{Energy Consumption}} + C_{\text{Tool Wear}} \tag{14}$$

$$C_{\text{Machining}} = \left(T_{\text{Machining}} \times R_{\text{Labor}}\right) + \left(T_{\text{Machining}} \times E_{\text{Machining}} \times P_{\text{Electricity}}\right) + \left(T_{\text{Machining}} \times M_{\text{Tools}}\right) \tag{15}$$

Whereas $T_{\text{Machining}}$ is the time required for machining, R_{Labor} represents the hourly labor rate, $E_{\text{Machining}}$ is the energy consumption rate during machining, $P_{\text{Electricity}}$ is the cost per unit of electricity, and M_{Tools} denotes the cost of tool wear per unit of time.

- **Heat Treatment Cost**

$$C_{\text{Heat Treatment}} = C_{\text{Labor}} + C_{\text{Energy Consumption}} \tag{16}$$

$$C_{\text{Heat Treatment}} = \left(T_{Furnace\ Setup\ Time} \times R_{\text{Labor}}\right) + \left(T_{\text{Heat Treatment}} \times E_{\text{Furnace}} \times P_{\text{Electricity}}\right) \tag{17}$$

Whereas $T_{\text{Heat Treatment}}$ is the time required for heat treatment, $T_{Furnace\ Setup\ Time}$ is the time required for the setting up the furnace, R_{Labor} represents the hourly labor rate, E_{Furnace} is the furnace's energy consumption rate during the heat treatment, and $P_{\text{Electricity}}$ denotes the cost per unit of electricity.

- **Surface Finishing Cost**

$$C_{\text{Surface Finishing}} = C_{\text{Labor}} + C_{\text{Consumables}} + C_{\text{Energy Consumption}} \tag{18}$$

$$\begin{aligned} C_{\text{Surface Finishing}} = {} & \left(T_{\text{Surface Finishing}} \times R_{\text{Labor}}\right) + \left(M_{\text{Consumables}} \times P_{\text{Consumables}}\right) \\ & + \left(T_{\text{Surface Finishing}} \times E_{\text{Finishing}} \times P_{\text{Electricity}}\right) \end{aligned} \tag{19}$$

Whereas $T_{\text{Surface Finishing}}$ is the time required for surface finishing, R_{Labor} represents the hourly labor rate, $M_{\text{Consumables}}$ is the amount of consumables such as abrasives used, $P_{\text{Consumables}}$ denotes the cost per unit of consumables, $E_{\text{Finishing}}$ is the energy consumption rate during surface finishing, and $P_{\text{Electricity}}$ represents the cost per unit of electricity.

3.1.6. AM Part Qualification Cost

$$\begin{aligned} C_{\text{Part Qualification}} = {} & C_{\text{Dimensional Inspection}} + C_{\text{Corrosion Resistance Test}} + C_{\text{Material Strength Test}} \\ & + C_{\text{Surface Hardness Test}} + C_{\text{Density Validation}} \end{aligned} \tag{20}$$

The $C_{\text{Dimensional Inspection}}$ represent the cost of verifying the part's dimensions to ensure they align with the design specifications. This typically involves using tools like calipers, micrometers, or Coordinate Measuring Machines (CMMs) to measure various features of the part. The $C_{\text{Corrosion Resistance Test}}$ accounts for the cost of evaluating the part's resistance to corrosion, which can involve exposure to salt spray tests, immersion tests, or other environmental conditions to simulate real-world usage. The $C_{\text{Material Strength Test}}$ covers the cost of assessing the mechanical strength of the part, typically using methods like tensile, compression, or impact testing to evaluate the material's ability to withstand force. The $C_{\text{Surface Hardness Test}}$ involves the cost of testing the part's hardness, usually done through methods such as Rockwell, Brinell, or Vickers tests to evaluate its wear resistance. Finally, the $C_{\text{Density Validation}}$ represents the cost of checking the part's density, ensuring proper material consolidation and quality.

4. Case Study

Three complex components from the oil and gas sector were selected for production using BMD technology to validate the cost estimation model. The parts were manufactured using a Desktop Metal Studio System 2 (Studio SystemTM) printer with 316L stainless steel as the primary material, chosen for its superior mechanical properties and corrosion resistance. The selected components - an impeller, a repair clamp, and an eccentric gear wheel, represent different levels of geometric complexity and size, providing a comprehensive validation spectrum for the cost estimation model.

Each component underwent a standardized manufacturing process comprising three main stages: BMD printing, debinding, and sintering. Each component underwent rigorous qualification testing appropriate to its intended application, including dimensional inspection using CMM, density verification, surface roughness measurements, and specific mechanical property validation tests. Table 2 contains the production related parameters of the three spare parts involved in the BMD process.

Table 2. Case study parameter values.

Parameter	**Impeller**	**Repair Clamp**	**Ecentric Gear Wheel**
Dimensions (mm)	79.75 × 79.72 × 35.42	79.10 × 76.77 × 50.42	138.34 × 137.90 × 61.82
Number of Layers	229	329	405
Final Part Weight (g)	239.06	303.12	1940
Metal Material Consumed (g)	373.93	441.38	2380
Ceramic Material Consumed (g)	2.51	1.84	3.47
Print Time (h)	20.68	21.47	81.05
Debind Time (h)	28.10	18.27	67.92
Sinter Time (h)	45.33	45.33	45.33

5. Results and Discussion

The cost estimate of the three parts, Impeller, Repair Clamp, and Eccentric Gear Wheel indicates different cost structures influenced by design complexity, material requirement, and processes. The stacked bar chart in Figure 2 presents a comparative cost analysis of the cost for production of three metallic spare parts through BMD. The Eccentric Gear Wheel exhibits the highest total cost at approximately $1,495, followed by the Impeller at $825, and the Repair Clamp at $600.

Manufacturing costs consistently represent the largest proportion across all components with a share of 36.8%, 47.9%, and 31.4% from the total cost of impeller, repair clamp and eccentric gear wheel respectively. Material costs vary significantly, being most substantial in the Eccentric Gear Wheel (20.1%) and lowest in the Impeller (5.7%). Post-processing costs also show considerable variation, reaching 22.7% for the Eccentric Gear Wheel but only 9.8% for the Repair Clamp. Design costs remain relatively consistent across components, while qualification costs show some variation, being highest in the Impeller (20.0%) and lowest in the Eccentric Gear Wheel (11.0%). This distribution suggests that while manufacturing processes dominate costs across all components, the specific cost allocations vary significantly based on component complexity and requirements (Figure 2).

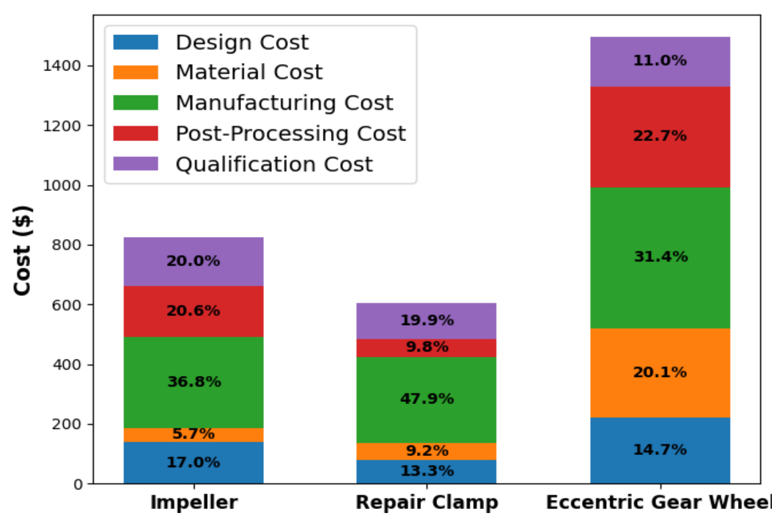

Figure 2. Cost breakdown of spare parts.

With its overall cost drive, the eccentric gear wheel of $1,495.59, complex and large structure raised the price of production. Manufacturing operations accounted for 31.4%, while printing and post-processing were a bit higher in comparison with the other parts. The post-processing cost was relatively high because of the intensive surface finishing and machining requirements. Moreover, the volume and weight of the gearwheel were higher, hence also the material cost (Table 3).

Table 3. Subcomponents' costs breakdown.

Cost Break Down	Impeller ($)	Repair Clamp ($)	Eccentric Gear Wheel ($)
Design Cost			
Scanner Cost	40	20	80
Software License Cost	20	20	20
Designer Cost	80	40	120
Material Cost			
Metal cost	46.62	55.12	297.50
Ceramic Cost	0.26	0.19	3.64
Manufacturing Cost			
Printing Cost	54.04	55.70	155.01
Debinding cost	46	29.998	110.97
Sintering cost	203.52	203.52	203.52
Post-processing cost			
Heat treatment	87.94	23.86	87.94
Machining	40.14	10.04	120.43
Surface finishing	41.72	25.32	131.58
Part qualification cost			
Dimensional inspection	30	30	30
Corrosion resistance Test	50	50	50
Material strength Test	40	40	40
Surface hardness Test	25	0	25
Density Validation Test	20	0	20
Total Cost	**825.26**	**603.74**	**1495.59**

The design costs for each component vary significantly, with the Eccentric Gear Wheel having the highest design costs at $220 (scanner cost $80, software license $20, designer cost $120), followed by the Impeller at $140 (scanner cost $40, software license $20, designer cost $80), and the Repair Clamp having the lowest at $80 (scanner cost $20, software license $20, designer cost $40). This cost variation directly reflects the geometric complexity of each component. The Repair Clamp exhibits the lowest design costs due to its relatively simple geometry, requiring minimal scanning and design time. In contrast, the Eccentric Gear Wheel and Impeller demand higher design investments due to their complex features – the Eccentric Gear Wheel with its precise gear geometries and the Impeller with its intricate flow channels and curved surfaces. These complex geometries necessitate more extensive scanning time for accurate digital representation and increased designer involvement to ensure proper modeling of all critical features.

Material costs show substantial differences, with the Eccentric Gear Wheel having significantly higher costs at $301.14 (metal cost $297.50, ceramic cost $3.64), while the Repair Clamp at $55.31 (metal cost $55.12, ceramic cost $0.19) and the Impeller at $46.88 (metal cost $46.62, ceramic cost $0.26) have much lower material costs. This substantial cost variation is primarily attributed to the size differences between components. The Eccentric Gear Wheel is considerably larger, requiring approximately six times more material volume compared to the other components.

Manufacturing costs consist of three main processes of printing, debinding, and sintering. Notably, sintering costs remain constant at $203.52 for all components as this process is primarily time-dependent rather than size-dependent, requiring the same furnace cycle regardless of component size. The main cost variations arise in printing and debinding, where the Eccentric Gear Wheel's larger size significantly impacts these processes.

Post-processing costs vary widely, with the Eccentric Gear Wheel having the highest at $339.95 (heat treatment $87.94, machining $120.43, surface finishing $131.58), followed by the Impeller at $169.80 (heat treatment $87.94, machining $40.14, surface finishing $41.72), and the Repair Clamp having the lowest at $59.22 (heat treatment $23.86, machining $10.04, surface finishing $25.32). The significant cost variations reflect the geometric complexity and finishing requirements of each component. The Eccentric Gear Wheel requires extensive machining and surface finishing due to its precise gear teeth geometry and critical mating surfaces, while the Impeller needs careful processing for its complex flow channels and blade surfaces. In contrast, the Repair Clamp's simpler geometry requires minimal post-processing, resulting in significantly lower costs across all post-processing operations. The heat treatment costs also vary based on the structural requirements, with both the Eccentric Gear Wheel and Impeller requiring more intensive heat treatment due to their operational demands.

Qualification costs are identical for the Impeller and Eccentric Gear Wheel at $165 (dimensional inspection $30, corrosion resistance test $50, material strength test $40, surface hardness test $25, density validation test $20), while the Repair Clamp has lower qualification costs at $120 (dimensional inspection $30, corrosion resistance test $50, material strength test $40, no surface hardness or density validation tests). This cost variation directly reflects the application-specific requirements and operational criticality of each component. The Impeller and Eccentric Gear Wheel require comprehensive testing due to their critical roles in fluid handling and power transmission respectively, necessitating additional surface hardness and density validation tests to ensure reliable performance under demanding conditions. The Repair Clamp, being a less dynamically stressed component, requires only basic structural and material validation tests, eliminating the need for advanced surface and density testing while still maintaining essential quality standards for its specific application.

5.1 Managerial Implications

This section overviews the key managerial implications based on the cost analysis presented.

Strategic Design Resource Allocation

The significant variation in design costs across components ($220 for Eccentric Gear Wheel vs. $80 for Repair Clamp) suggests the need for a strategic approach to design resource allocation. Managers should implement a tiered design process where complex components receive proportionally higher resource allocation, while maintaining efficient utilization of design resources for simpler components. This approach would optimize the balance between design quality and cost efficiency across different component complexities.

Post-Processing Cost Management Framework

The wide disparity in post-processing costs indicates the need for a comprehensive post-processing management framework. Managers should develop targeted optimization strategies for complex components, focusing on streamlining machining and surface finishing operations while maintaining quality standards. This could include investing in advanced automation technologies for complex geometries while utilizing standard processes for simpler components.

Quality Assurance Cost Optimization

The selective application of qualification tests across components demonstrates the potential for application- specific quality assurance protocols. Management should develop a risk-based testing framework that aligns qualification requirements with component criticality, ensuring comprehensive testing for critical components while optimizing costs for less demanding applications without compromising essential quality standards.

6. Conclusion

This study presents a comprehensive process-based cost analysis model for MAM in spare parts production, providing valuable insights into the economic implications. The findings demonstrate significant cost variations driven by geometric complexity and size differences, with manufacturing costs constituting the largest portion of total expenses. While this research contributes to understanding MAM economics, several limitations should be acknowledged. The analysis is based on current technology and process parameters, focuses on a limited number of components, and does not account for potential economies of scale or environmental impacts. Future research could address these limitations by investigating the impact of technological advancements on cost structures, exploring cost optimization through process parameter optimization, integrating sustainability metrics, and examining the relationship between production volume and cost efficiency. Additionally, developing standardized qualification procedures and integrating this cost model with supply chain simulation tools could further enhance the understanding of MAM implementation in spare parts networks.

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Biographies

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Regina Padmanabhan is a researcher specializing in the intersection of artificial intelligence, mathematical modeling, and its application in healthcare, logistics, and supply chain management. With a Ph.D. in Electrical Engineering, her expertise lies in developing innovative solutions for real-time problems using cutting-edge methods such as reinforcement learning and machine learning. With over 10 years of research experience, she has demonstrated exceptional proficiency in study design, data interpretation, and evidence-based decision-making, resulting in numerous international publications. Additionally, she has 5 years of teaching and mentoring experience. Currently, Dr. Padmanabhan serves as a postdoctoral fellow in the Division of Engineering Management and Decision Science at Hamad Bin Khalifa University.

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Marwan Khraisheh is Professor and Associate Dean for Faculty Affairs at the College of Science and Engineering, Hamad bin Khalifa University, Qatar. He is a Fellow of the American Society of Mechanical Engineers (ASME) and the American Association for the Advancement of Science (AAAS) and a member of the International Academy for Production Engineering (CIRP). He earned his PhD in Mechanical Engineering from Washington State University in 1996 and worked in the United States, building expertise in advanced manufacturing and materials. He also served as the Founding Dean of Masdar Institute in Abu Dhabi and worked with MIT to help establish graduate programs in sustainable technologies and build a strong academic and research community. As Chair of Mechanical Engineering at Texas A&M University at Qatar, he focused on developing smart and sustainable manufacturing programs. Professor Khraisheh has received several international recognitions, including the US National Science Foundation Career Award and the SME's Eugene Merchant Outstanding Young Manufacturing Engineer Award.

Adel Elomri is an Associate Professor of Logistics and Supply Chain Management at Hamad Bin Khalifa University's College of Science and Engineering. He holds a Ph.D. and MSc in Operations Management from CentraleSupélec Paris and a BSc in Industrial Engineering from the National Engineering School of Tunisia. With over 15 years of international experience in lecturing and research, Elomri specializes in modeling and analyzing supply chain networks, including healthcare operations management, sustainable supply chain management, smart logistics, and production and operations management.

Laoucine Kerbache is full Professor of Logistics and Supply Chain Management and a founding member of the Engineering Management and Decisions Science (EMDS) Division within the College of Sciences and Engineering (CSE, HBKU) since 2018. In addition, over the last 35 years, Dr. Kerbache has been in academia (teaching and research) with 24 years at HEC Paris where he was full Professor of Operations management, Logistics, and Supply

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