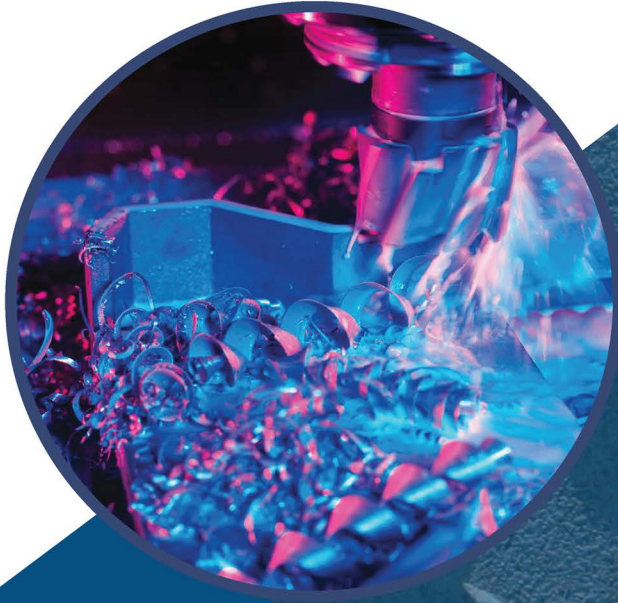


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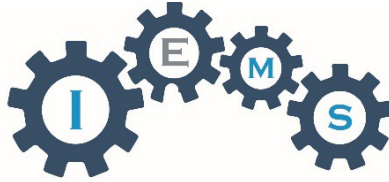


I E M S
2025
#31

ISSN 2690-3210 (Print)
ISSN 2690-3229 (online)

PROCEEDINGS

OF THE
INTERNATIONAL
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INDUSTRY, ENGINEERING & MANAGEMENT SYSTEMS CONFERENCE

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INVESTIGATION OF OPTICAL AND MECHANICAL PROPERTIES OF GOLD-COATED POLYCARBONATE AND CAST ACRYLIC TRANSPARENT COMPOSITES FOR AEROSPACE APPLICATIONS

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Abstract

Transparent polymers like polycarbonate (PC) and cast acrylic (CA) are widely used in aerospace due to their light weight, impact resistance, and optical clarity. However, there is limited information on how coatings affect their mechanical and optical properties. This study aims to assess the impact of heat treatment and gold coatings on the hardness and light transmittance of PC and CA. PC was cut using waterjet, and CA was laser-cut. After cutting, both materials underwent heat treatment at 150°C, followed by gold coating using magnetron sputtering. Vickers hardness tests and optical transmittance measurements were used to analyze the results. Key findings show that heat treatment increased the hardness of CA by 15.6% and PC by 16.9%. Gold coating further boosted hardness by 13.8% for CA and 20% for PC. In terms of light transmission, uncoated CA allowed over 90% of visible light through, which dropped to 30–70% after coating. Similarly, PC's transmittance fell from 90% to 20–50% after coating. The gold coating also provided effective UV protection for both materials. These improvements in hardness and UV protection make coated PC and CA promising materials for aerospace applications.

Keywords: *Transparent Polymers; Polycarbonate (PC); Cast Acrylic (CA); Gold Coating; Optical Transmittance.*

1. Introduction

Transparent polymers are the key components in the design of optically transparent polymer composites. The overall transparency of a material can be defined by its ability to allow visible light to pass through. Transparency is a unitless measure, typically expressed as a percentage of the ratio of transmitted light to incoming light. Several factors, such as reflection, absorption, and scattering, affect the degree of transparency of a material. To achieve maximum transparency, it is important to minimize these factors. Although inorganic glass is widely used as a highly transparent material, its brittle nature and low impact resistance raise safety concerns regarding its use (Kumar & Kumar, 2023). Therefore, transparent polymeric materials are increasingly being used as a replacement for glass due to their advantageous properties such as high impact resistance, flexibility, low density, high strength-to-weight ratio, and rapid production (Meinders, Murphy, Taylor, Chandrashekhara, & Schuman, 2021). Polymers can be divided into two groups based on their degree of crystallinity: semi-crystalline polymers and amorphous polymers. While amorphous polymers consist entirely of randomly arranged polymer chains, semi-crystalline polymers are composed of both random and ordered polymer chains or regions of crystalline and amorphous areas. The different properties exhibited by these polymers based on their degree of crystallinity are particularly important in terms of transparency. In semi-crystalline polymers, the boundaries between amorphous and crystalline regions can cause light scattering, thereby reducing transparency. On the other hand, amorphous polymers can achieve transparency if there are no visible defects (Giles Jr, Wagner Jr, & Mount III, 2005).

In this context, amorphous polymers such as polycarbonate (PC) and polymethyl methacrylate (PMMA) stand out as ideal materials for many applications. Polycarbonate laminates have become the most preferred material for windshield construction due to their lightness, transparency, extreme ductility, dimensional stability, excellent heat and temperature resistance, high tensile and compressive strength, superior impact resistance, and excellent shear loading properties. Polycarbonates are highly suitable for structural applications due to their light weight, high durability, and excellent rigidity (Umeno, Kubo, & Albina, 2020). In addition to structural applications, polycarbonate is also widely used in optical applications (Eggenhuisen & Hoeks, 2022). Improving the mechanical properties of PC prevents windshield failure by increasing impact absorption. Ultraviolet (UV) rays at certain wavelengths have a significant impact on the mechanical properties of polycarbonate, as they can break molecular bonds; however, in general, PC molecules comfortably absorb incoming UV rays, allowing only visible light to pass through the structure (Aflug, Hachim, Ibrahim, & Alalwan, 2021).

On the other hand, polymethyl methacrylate (PMMA) is known for its wide range of applications due to its good optical clarity, weather resistance, mechanical properties, and chemical stability. One of the most important applications of PMMA is in aircraft cockpit canopies. Most PMMA applications are exposed to harsh environmental conditions such as ultraviolet (UV) rays, heat, humidity, cleaning agents, residual stress during molding, and wind, which can lead to crazing. Additionally, aircraft cockpit canopies are subjected to cumulative effects such as total stress from the fuselage structure, pressure differences between the inside and outside of the cockpit, and the aerodynamic force of the wind (Wang et al., 2015). Crazing, a network of densely stretched microfibers about 0.5 microns wide that are crack-like defects in polymers, has been a subject of research for 50 years (Clay & Kander, 2001). One reason for such widespread interest is that these defects are often crack initiation points and frequently lead to brittle fracture in otherwise ductile polymers. Crazing is a form of localized plastic deformation rather than mechanical cracking (Ishikawa, Sato, & Higuchi, 1996; Weber, 1926). Crazes are easily visible to the naked eye because

they reflect light from their surfaces and appear as bright (silvery) streaks or spots when the cockpit is held at different angles. As a result, crazing obstructs the pilot's forward vision during flight. It is known that crazes initiate at defects (voids) for various reasons, propagate perpendicular to the axis of applied stress, and ultimately tear under sufficiently high stress. At the low stresses experienced by the cockpit, failure due to structural inadequacy is unlikely. Therefore, the primary concern is the pilots' ability to see clearly through the cockpit (Kim, Cho, Sohn, Kim, & Kim, 2021).

Transparent conductive film (TCF) materials are widely used in electronic and optoelectronic devices, including applications such as touch screens, display technologies, smart windows, and wearable flexible devices (Morales-Masis, De Wolf, Woods-Robinson, Ager, & Ballif, 2017; Yu, Liu, et al., 2021). In aircraft cockpits, TCFs provide functions like dissipating static electricity, de-icing, and offering electromagnetic interference (EMI) protection, while also ensuring maximum visibility for pilots (Jenifer & Parthiban, 2023; Pötschke & Pionteck, 2016; Yu, Li, Zhao, Gong, & Li, 2021). The TCF coatings used in cockpits must be processed at low temperatures and possess durability (Bruyn Neto, Sales, Iha, & Rocco, 2016). Commercial transparent electrodes used in aircraft cockpits generally contain oxide layers (ITO, AZO, ZTO, BiO), while the combination of ultrathin metal film (UTMF) with transparent conductive oxide (TCO) thin films has gained popularity recently (Girtan & Negulescu, 2022). OMO (oxide/metal/oxide) structures offer optical and electrical properties thanks to the conductivity of the embedded UTMF, along with flexibility and stability (Morales-Masis et al., 2017; Zilberberg & Riedl, 2016). The position and thickness of the metal layers play a critical role in determining the optoelectronic properties of these films (Ferhati & Djeflal, 2020; Yu, Li, Lyu, & Zhang, 2016). Ultrathin metal films like silver (Ag), gold (Au), and copper (Cu) generally provide low sheet resistance; however, Ag and Cu may oxidize over time, degrading their optical and electrical performance (Dimopoulos et al., 2015; Jenifer & Parthiban, 2023). Despite its high cost, gold is preferred for its resistance to corrosion and oxidation, durability, and radar attenuation properties (Dimopoulos et al., 2015; Erdogan et al., 2020).

In this study, optically transparent composites were used, specifically polycarbonate (PC) and cast acrylic (CA) laminates from the polymethyl methacrylate (PMMA) group. The cutting processes for the transparent composite laminates were conducted using waterjet cutting for polycarbonate and laser cutting for cast acrylic. To minimize potential damage during the cutting process, the laminates underwent thermal treatment, and the cut surfaces were examined. Additionally, PC and CA substrates were coated with a gold (Au) metal layer using the magnetron sputtering method as a preliminary step for multi-layer thin film coatings. Subsequently, the UV visibility properties of the gold-coated samples were investigated, and the changes in hardness values before and after coating were examined. In this context, the results demonstrated whether the coatings were suitable for providing sufficient protection without obstructing the pilot's view inside the cockpit and ensuring long-term durability. The ultimate goal of the study is to contribute to the development of economical, durable, and high-performance transparent composite materials for aircraft cockpits.

2. Experiment

2.1. Materials

In this research, two types of transparent polymers, polycarbonate and cast acrylic, were procured. The polycarbonate material, SABIC LEXAN 9030, was obtained from Spinside, while the cast acrylic, Clear Poly 84, was acquired from Spartech. Both transparent sheets measured 36 x 48 x 0.250 inches in size. The typical properties of polycarbonate and cast acrylic are listed in Tables 1 and 2, which were compiled directly from the Product Datasheets provided by the respective suppliers (SABIC and Spartech). Additionally, the sandpaper required for surface sanding was

purchased from Home Depot.

2.2. Cutting Processes

Cast acrylic sheets were cut using a laser cutting process, while polycarbonate sheets were cut using a water jet cutter. Each sample was cut into dimensions of 2" × 2". Both cutting processes were carried out at GoCreate, located in the John Bardo Center at Wichita State University. The cast acrylic sheets were cut using an Epilog Laser Fusion Pro Model 16000 (Figure 1(a)), with laser cutting parameters set at 20% speed, 100% power, and 50% frequency, as shown in Figure 1(b). For polycarbonate sheets, a water jet cutter (Figure 1(c)) was used, operating with a pressure range of 18-45 103 PSI, an abrasive flow rate of 0.56 lb/min, and a cutting speed of 162.5 inches/min. The water jet cutting process is depicted in Figure 1(d). Following the cutting, the polycarbonate and cast acrylic sheets are displayed in Figure 2.

Table 1. Physical and Mechanical Properties of Polycarbonate Laminate

PROPERTY	TEST METHOD	UNITS	LEXAN 9030
Specific Gravity	ASTM D792	-	1.20
Refractive Index @ 77°F	ASTM D542A	-	1.586
Light Transmission (Average at 0.118")	ASTM D1003	%	86
Initial Haze		HU	<1
Rockwell Hardness (M scale)	ASTM D785	-	70
Rockwell Hardness (R scale)	ASTM D785		118
Taber @ 100 cycles	ASTM D1044	% haze	10
Water Absorption, 24 hrs	ASTM D570	%	0.15
Water Absorption, Equilibrium @ 73°F		%	0.35
Tensile Strength, Yield	ASTM D638	psi	9,500
Tensile Modulus	ASTM D638	psi	345,000
Flexural Strength	ASTM D790	psi	13,500
Flexural Modulus	ASTM D790	psi	345,000
Compressive Strength	ASTM D695	psi	12,500
Compressive Modulus	ASTM D695	psi	345,000
Poisson's Ratio	ASTM E132	-	0.37

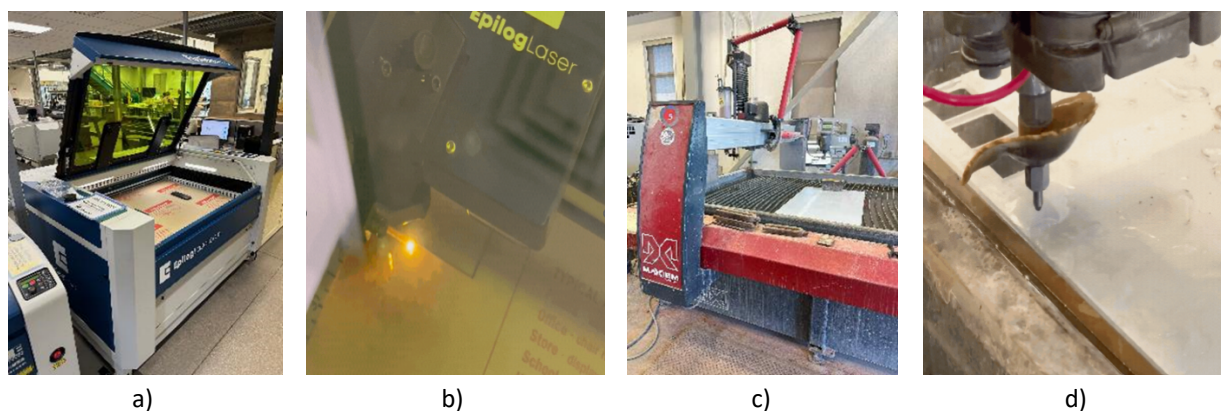


Figure 1. Experimental Observations from Cutting Operations (A) Epilog Laser Fusion Pro Laser Cutting Apparatus, (B) Laser Cutting of Cast Acrylic Sheet, (C) Water Jet Cutting Apparatus, (D) Water Jet Cutting of Polycarbonate Sheet

Table 2. Physical and Mechanical Properties of Cast Acrylic Laminate

PROPERTY	TEST METHOD	UNITS	POLY 84
Specific Gravity	ASTM D792	-	1.19
Refractive Index	ASTM D542A	-	1.49
Light Transmission	ASTM D1003	%	92
Initial Haze		HU	<0.75
Rockwell Hardness (M scale)	ASTM D785	-	M98
Barcol Hardness	ASTM D-2583		50
Water Absorption, 24 hrs	ASTM D570	%	0.2
Water Absorption, Equilibrium		%	1.6
Tensile Strength,at Break	ASTM D638	psi	11,250
Tensile Modulus	ASTM D638	psi	450,000
Flexural Strength	ASTM D790	psi	15,250
Flexural Modulus	ASTM D790	psi	450,000
Compressive Strength	ASTM D695	psi	18,000
Compressive Modulus	ASTM D695	psi	440,000
Poisson's Ratio	ASTM E132	-	0.37

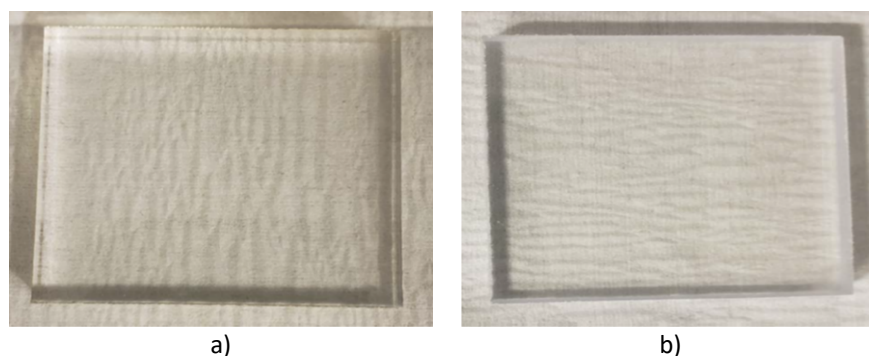


Figure 2. Sample Image After Cutting Processes (A) Cast Acrylic, (B) Polycarbonate

2.3. Sample Preparations and Gold (Au) Coating

Following the laser and waterjet cutting processes, the cut edges of the cast acrylic and polycarbonate sheets were sanded using sandpapers of different grit sizes to remove contaminants and eliminate surface irregularities caused by cutting, and the samples were subjected to a heat treatment at 150°C. These irregularities can weaken the material and lead to damage propagation under stress during use. To address this, the edges of the transparent polymer sheets were progressively sanded using sandpapers with grit sizes of 400, 1000, and 1500, ensuring a smoother surface finish and improved durability.

The samples were coated with gold at the NIAR Advanced Coating Laboratory using a sputter coater. This involved two pieces of 2" x 2" Cast Acrylic and polycarbonate. One sample from each material served as a reference, while the remaining samples were designated for testing. Initially, the provided samples were cleaned using isopropyl alcohol, followed by plasma treatment on the testing samples to activate their surfaces. After activation, the samples were placed in the sputter coater, where a thin gold layer was applied. The coating process occurred at a room temperature of 76.2 °F with a humidity level of 42.2% RH. Table 3 below illustrates the approximate thickness of the gold layer that was applied. The sputter coater operates at low voltage, and the gold coating was applied following a pulse cleaning procedure utilizing compressed gas. The sputter coating resulted in different thicknesses for cast acrylic (5 nm) and polycarbonate (12 nm), depending on the adhesion and stability requirements of each substrate in Table 3. It should be noted that, at the nanometer scale, controlling the exact coating thickness is challenging due to process-related factors such as sputtering time, target-substrate distance, and particularly the sensitivity of the substrates to prolonged exposure. Therefore, minor variations in the achieved thickness values are inevitable and must be considered when interpreting the results.

Table 3. Sample Details for Gold Coating Thickness and Plasma Treatment

<i>Samples</i>	<i>Coating Thickness</i>	<i>Time between treatment and coating</i>
<i>Cast Acrylic Ref</i>	--	--
<i>Cast Acrylic – Gold coated</i>	~5.2 nm	~20 mins
<i>Polycarbonate Ref</i>	--	--
<i>Polycarbonate - Gold Coated</i>	~12.3 nm	~ 35 mins

2.4. Characterization Testing

2.4.1. UV-Vis-IR Test

The samples underwent testing using UV-Vis-IR spectroscopy to compare light transmittance between the reference and coated samples across a wavelength range of 250 nm to 3300 nm. This analysis assesses the transmission or absorption of ultraviolet, visible, and infrared light by the material. The resulting spectra offer insights into the molecular and electronic properties of the samples evaluated.

2.4.2. Hardness Tests

The Vickers Microhardness test was conducted to assess the hardness of the polymer laminates in this study. This test followed the ASTM E384 standards, which require the sample thickness to be at least ten times the indentation depth to ensure accurate results. The hardness values were measured using a Wilson VH 1202 bench-top hardness tester, applying an HV1 load of 1 kgf on the samples (Figure 3). A 10x microscopic lens was employed to accurately measure the length of the indentations created during the testing process. For each condition, hardness measurements were performed on a single cast acrylic and a single polycarbonate sheet, with five repeated indentations taken from different points on the surface to obtain representative average values.



Figure 3. Vickers Hardness Tests for Polymer Laminates

2.5. Microscopic Surface Examinations

Optical images of polycarbonate and cast acrylic test coupons have been obtained using a ZEISS Axio Imager to observe how the cutting processes, heat treatments and sanding physically affect the surfaces.

3. Results and Discussion

The images of the cutting surfaces of PC and CA samples, before and after the 150°C heat treatment and sanding processes, are presented in Figure 4. Although coating processes will be performed on the surfaces of the samples, any notches, cracks, or other damage on the cutting edges can potentially

propagate and damage the surface coatings during service. Therefore, to minimize such damage on the cutting surfaces, heat treatment and sanding processes were applied to the cut edges of the samples. In the images taken immediately after the laser cutting of the CA samples, significant surface damage is evident (Figure 4a). Additionally, burn marks caused by the heat from the laser can be observed in areas where void-like defects are present. Moreover, the surface exhibits plastic deformation in the form of noticeable wave patterns. After the heat treatment and sanding processes, it is observed that the wave-like plastic deformation has nearly disappeared, and the void defects have been significantly minimized. It can also be seen in Figure 4b that the remaining defects have reduced in size. In the case of the PC samples, noticeable regions of rough plastic deformation are evident after waterjet cutting (Figure 4c). Following similar surface treatment processes, the PC samples achieved an almost ideal surface condition, as shown in Figure 4d. In conclusion, the heat treatment and sanding processes successfully eliminated the damage caused by the cutting operations on the transparent polymer laminates, resulting in clean and smooth cutting edges.

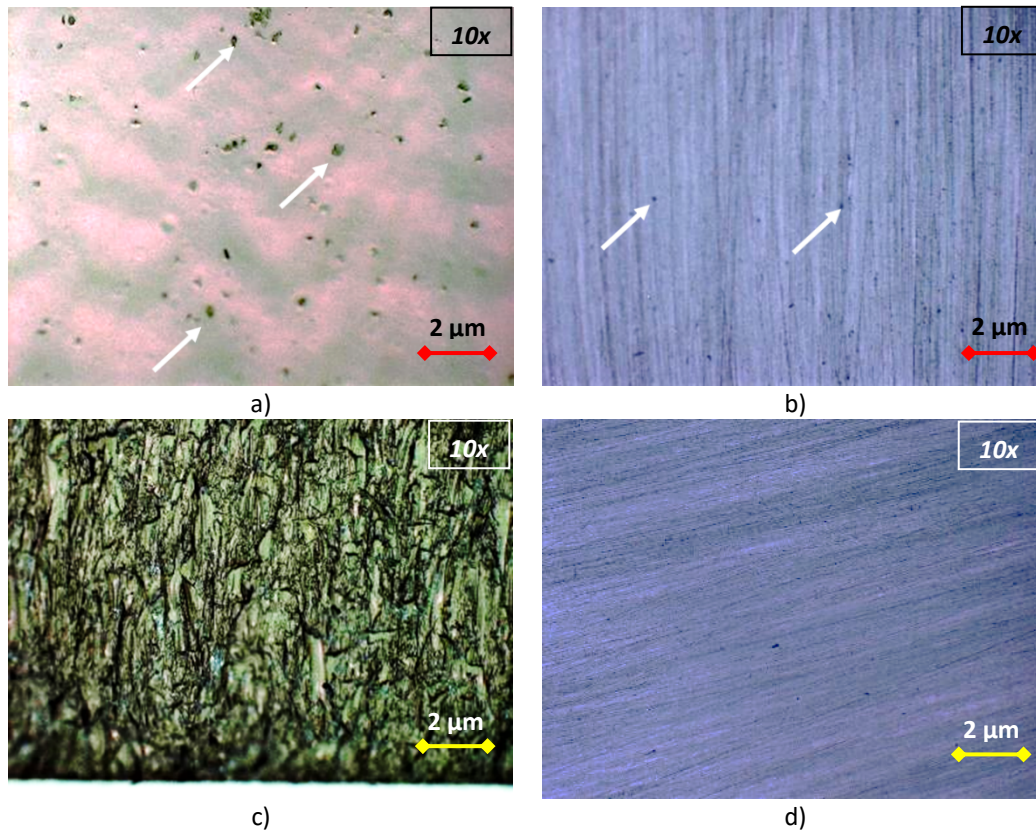


Figure 4. The Cutting Surfaces of The Samples Before and After the Heat Treatment and Sanding Processes A) CA Before Treatment CA B) CA After Treatment CA C) PC Before Treatment PC D) PC After Treatment

The light transmittance differences and characteristics of the reference cast acrylic and polycarbonate samples, as well as their gold-coated counterparts, across wavelengths ranging from 300 nm to 3300 nm are illustrated in Figure 5. The reference cast acrylic sample exhibits a very high transmittance, exceeding 90% in the visible light region (400-800 nm). This indicates that uncoated cast acrylic allows almost all visible light to pass through, making it highly transparent (Figure 5a). In contrast, the gold-coated cast acrylic sample shows significantly lower transmittance, ranging from

~30% to 70%, in the same region. Furthermore, in the ultraviolet (UV) range, the gold coating largely absorbs UV rays, forming a protective barrier against UV radiation. A similar protective effect is observed in the polycarbonate (PC) samples, as shown in Figure 5b. The gold-coated PC sample demonstrates very low transmittance in the UV region, effectively blocking UV radiation. Additionally, the uncoated PC sample shows a high transmittance (~90%) across the visible spectrum. However, for the gold-coated PC sample, the visible light transmittance drops to around 20-50%, indicating that the gold coating significantly restricts light transmission by increasing reflection and absorption. In previous studies, Jennifer and Parthiban aimed to determine the transparent properties of multilayered conductive thin film coatings, where zinc tin oxide and gold (Au) were used as metal oxide layers. They identified the thickness of the Au layer as 8 nm, 10 nm, and 12 nm, concluding that the lowest optical transmittance was achieved with a 12 nm thick layer. Additionally, they observed that the transmittance properties of metal-coated surfaces were weakened compared to uncoated samples (Jennifer & Parthiban, 2023). In another study where silver (Ag) was used as the metal layer, the optical properties of ITO/Ag/ITO multilayer structures were examined as a function of the thicknesses of Ag and ITO films. It was found that the transmittance primarily depended on the Ag film thickness, while the wavelength range where maximum transmittance was achieved could be adjusted by modifying the ITO film thickness (Guillén & Herrero, 2009).

The Vickers hardness values obtained from tests on polycarbonate (PC) and cast acrylic (CA) polymer sheets are illustrated in Figure 6. Initially, the uncoated samples of CA and PC exhibited average hardness values of 13.71 HV and 9.87 HV, respectively. These results highlight the inherent differences between the two materials. Cast acrylic, with a higher hardness, indicates a more brittle but harder structure compared to polycarbonate. On the other hand, polycarbonate's lower hardness value suggests that it is more flexible and impact-resistant, making it suitable for applications where durability against mechanical impact is essential, while CA would be advantageous in environments requiring harder surfaces. Upon heat treatment at 150°C, there was a noticeable improvement in the hardness of both materials. The hardness of cast acrylic increased from 13.71 HV to 15.85 HV, reflecting an approximately 15.6% rise. This enhancement is likely due to increased polymer chain ordering and a reduction in stress concentration points, which contributes to a stronger surface. Similarly, polycarbonate's hardness increased from 9.87 HV to 11.54 HV after heat treatment, marking a 16.9% increase. Therefore, the impact of heat treatment was slightly more significant in polycarbonate than in cast acrylic, although CA maintained higher absolute hardness values overall. It should be emphasized that this increase in hardness is primarily attributed to the heat treatment process, while the gold coating provided only an additional and relatively minor improvement. After coating with a 5 nm gold film, cast acrylic's hardness increased by 13.8%, reaching 15.59 HV. Polycarbonate, coated with a thicker 12 nm gold film, showed an even more substantial increase of nearly 20%, with its hardness rising to 11.75 HV. The difference in coating thickness between CA and PC was primarily due to optimization during sputtering, as PC required a thicker layer for stable coverage. In addition, precise control of nm-level thickness is inherently difficult over extended deposition durations, which can lead to slight deviations in the coating uniformity and final thickness. The observed contribution of the gold layer was secondary compared to heat treatment, and the higher increase in PC can be partially explained by the thicker coating applied. Both heat treatment and gold coating enhanced the Vickers hardness of the transparent polymer composites, but heat treatment was the dominant factor responsible for hardness improvement.

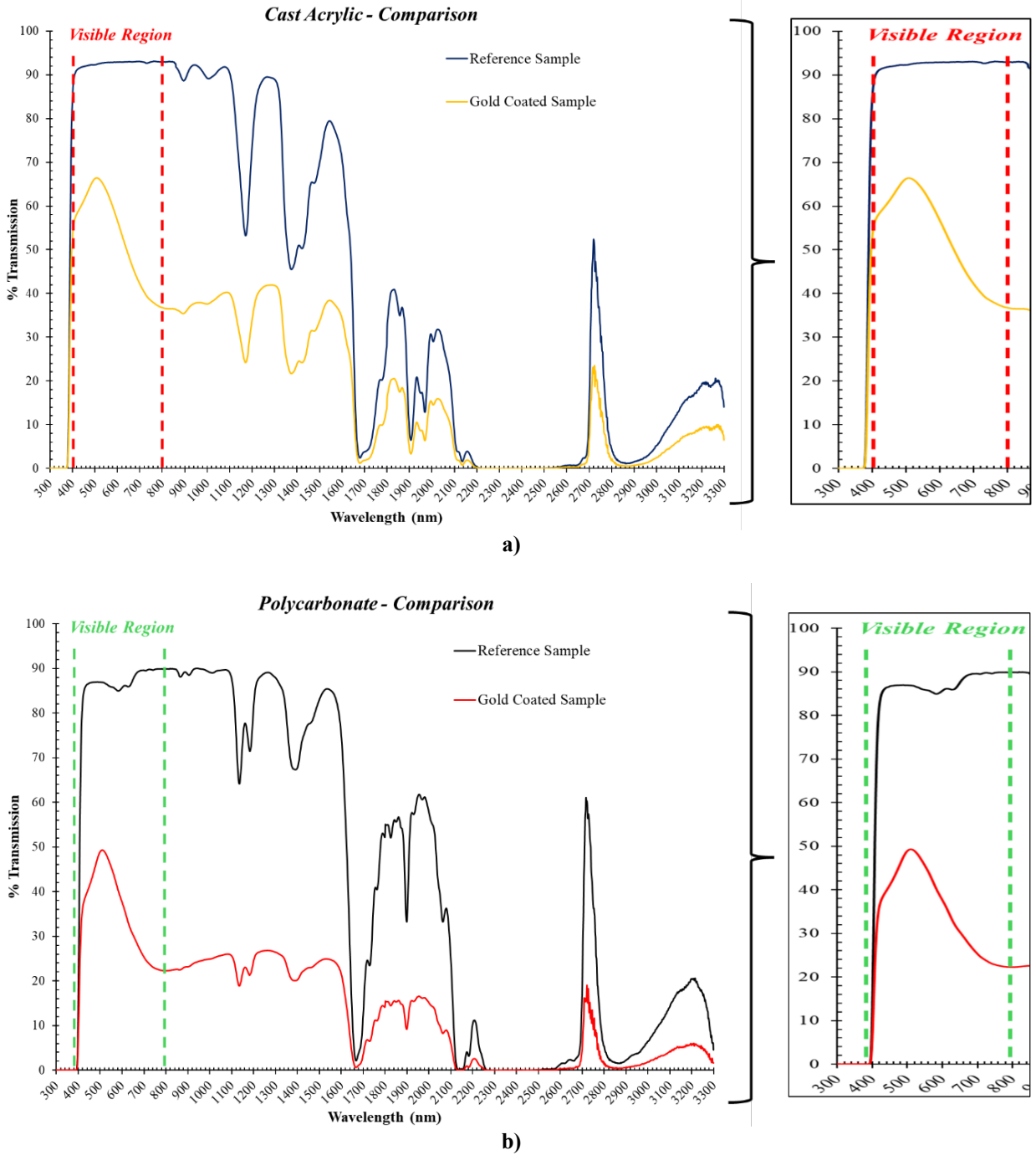


Figure 5. UV-Vis-IR Spectrophotometer Results A) Cast Acrylic - Ref and Gold Coat Comparison B) Polycarbonate- Ref and Gold Coat Comparison

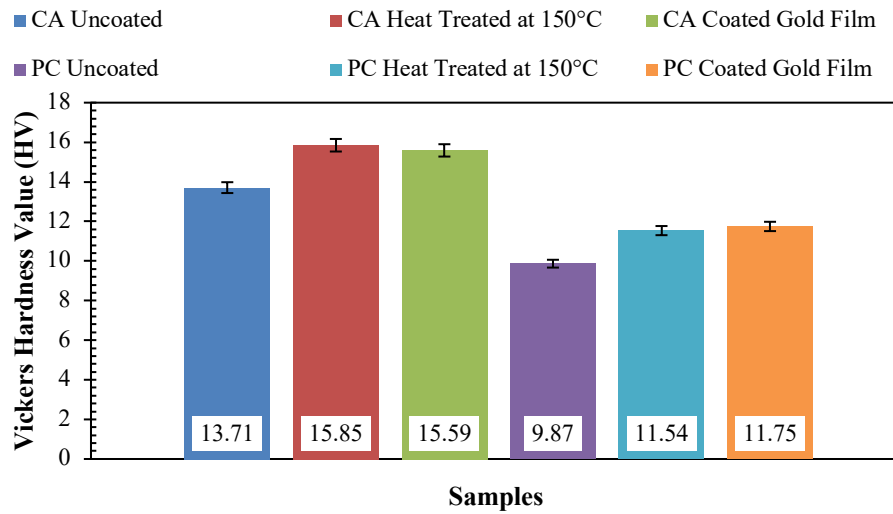


Figure 6. Vickers Hardness Test Results of Transparent CA and PC Polymer Laminates

4. Conclusions

In this study, the effects of heat treatment and gold coating on the mechanical and optical properties of transparent polycarbonate (PC) and cast acrylic (CA) laminates were investigated. The results demonstrate that both thermal processing and the application of a gold coating can significantly enhance the durability and hardness of these materials, which are essential for aerospace applications, particularly in aircraft cockpits where transparency and mechanical strength are critical. The Vickers hardness tests revealed that heat treatment at 150°C improved the hardness of both materials. Cast acrylic (CA) exhibited a more pronounced response to heat treatment, increasing its hardness by approximately 15.6%, while polycarbonate (PC) showed a 16.9% increase. This suggests that CA may be more susceptible to structural changes under thermal processes, enhancing its hardness. Additionally, the gold coating applied via magnetron sputtering further increased the hardness of both materials. The cast acrylic samples, coated with a 5 nm gold film, showed a 13.8% increase in hardness, while the polycarbonate samples, with a thicker 12 nm coating, demonstrated a nearly 20% improvement. The greater increase observed in PC could be attributed to the thicker gold coating, which not only improved the mechanical properties but also contributed to the surface durability. The optical properties of the materials were also influenced by the gold coating. Both PC and CA exhibited reduced transmittance in the visible light range, with the gold-coated samples blocking a significant portion of UV radiation. This is a valuable characteristic for applications where UV protection is required, such as in aircraft cockpits. Consequently, the combination of heat treatment and gold coating effectively enhanced the mechanical strength, durability, and UV-blocking capabilities of the transparent polymer laminates. These findings contribute to the ongoing development of high-performance, durable, and optically transparent materials for aerospace applications, specifically for ensuring the long-term reliability and safety of aircraft cockpit components.

5. Acknowledgments

The authors greatly acknowledge Wichita State University and Turkish Aerospace Industries – USA (TAI – USA) for the technical support of the present study.

6. Disclaimer Statements

Funding: Wichita State University and Turkish Aerospace Industries – USA (TAI – USA)

Conflict of Interest: None

7. References

- Afluq, S. G., Hachim, M. F., Ibrahim, Z. K., & Alalwan, H. A. (2021). Reinforcing the mechanical properties of windshield with interlayer-polycarbonates glass composite. *Journal of Engineering Science and Technology*, 16(5), 4192-4204.
- Bruyn Neto, M. D., Sales, R. d. C. M., Iha, K., & Rocco, J. A. F. F. (2016). Reinforced Transparencies for Aerospace Application–Case Description. *Journal of Aerospace Technology and Management*, 8, 49-54. <https://doi.org/10.5028/jatm.v8i1.575>
- Clay, S. B., & Kander, R. G. (2001). A new method to quantify crazing in various environments. *Polymer Engineering & Science*, 41(3), 401-407. <https://doi.org/10.1002/pen.10737>
- Dimopoulos, T., Bauch, M., Wibowo, R. A., Bansal, N., Hamid, R., Auer, M., . . . List-Kratochvil, E. (2015). Properties of transparent and conductive Al: ZnO/Au/Al: ZnO multilayers on flexible PET substrates. *Materials Science and Engineering: B*, 200, 84-92. <https://doi.org/10.1016/j.mseb.2015.06.008>
- Eggenhuisen, T., & Hoeks, T. (2022). Degradation mechanisms of aromatic polycarbonate. In *Reliability of Organic Compounds in Microelectronics and Optoelectronics: From Physics-of-Failure to Physics-of-Degradation* (pp. 33-52): Springer. https://doi.org/10.1007/978-3-030-81576-9_2
- Erdogan, N., Erden, F., Astarlioglu, A. T., Ozdemir, M., Ozbay, S., Aygun, G., & Ozyuzer, L. (2020). ITO/Au/ITO multilayer thin films on transparent polycarbonate with enhanced EMI shielding properties. *Current Applied Physics*, 20(4), 489-497. <https://doi.org/10.1016/j.cap.2020.01.012>
- Ferhati, H., & Djeflal, F. (2020). Performance assessment of TCO/metal/TCO multilayer transparent electrodes: from design concept to optimization. *Journal of Computational Electronics*, 19(2), 815-824. <https://doi.org/10.1007/s10825-020-01459-9>
- Giles Jr, H. F., Wagner Jr, J. R., & Mount III, E. M. (2005). 1-Extrusion Process. *Extrusion*. Norwich, NY, 1-8. <https://doi.org/10.1016/B978-1-4377-3481-2.00001-6>
- Girtan, M., & Negulescu, B. (2022). A review on oxide/metal/oxide thin films on flexible substrates as electrodes for organic and perovskite solar cells. *Optical Materials: X*, 13, 100122. <https://doi.org/10.1016/j.omx.2021.100122>
- Guillén, C., & Herrero, J. (2009). Transparent conductive ITO/Ag/ITO multilayer electrodes deposited by sputtering at room temperature. *Optics Communications*, 282(4), 574-578. <https://doi.org/10.1016/j.optcom.2008.10.075>
- Ishikawa, M., Sato, Y., & Higuchi, H. (1996). Effect of intermolecular interactions on the plastic deformation of glassy polymers. *Polymer*, 37(7), 1177-1181. [https://doi.org/10.1016/0032-3861\(96\)80844-5](https://doi.org/10.1016/0032-3861(96)80844-5)
- Jenifer, K., & Parthiban, S. (2023). Highly stable, ultra-thin Au embedded zinc tin oxide multilayer transparent conductive thin films. *Current Applied Physics*, 53, 94-103. <https://doi.org/10.1016/j.cap.2023.07.001>
- Kim, I.-S., Cho, H., Sohn, K.-S., Kim, K., & Kim, S. (2021). A study on the severe crazing phenomenon of the PMMA canopy under prolonged exposure to tropical climates. *Engineering Failure Analysis*, 129, 105719. <https://doi.org/10.1016/j.engfailanal.2021.105719>
- Kumar, A., & Kumar, N. (2023). A review on the electrically conductive transparent polymer composites: Materials and applications. *Materials Today: Proceedings*. <https://doi.org/10.1016/j.matpr.2023.07.211>
- Meinders, R., Murphy, D., Taylor, G., Chandrashekhara, K., & Schuman, T. (2021). Development of fiber-reinforced transparent composites. *Polymers and Polymer Composites*, 29(9_suppl), S826-S834. <https://doi.org/10.1177/09673911211023031>
- Morales-Masis, M., De Wolf, S., Woods-Robinson, R., Ager, J. W., & Ballif, C. (2017). Transparent electrodes for efficient optoelectronics. *Advanced Electronic Materials*, 3(5), 1600529. <https://doi.org/10.1002/aelm.201600529>
- Pötschke, P., & Pionteck, J. (2016). Mechanisms of Action of Antistatic Agents. In *Handbook of Antistatics* (pp. 83-101): Elsevier.

- Umeno, Y., Kubo, A., & Albina, J.-M. (2020). Coarse-grained molecular dynamics simulation of deformation and fracture in polycarbonate: Effect of molar mass and entanglement. *Theoretical and Applied Fracture Mechanics*, 109, 102699. <https://doi.org/10.1016/j.tafmec.2020.102699>
- Wang, X., Wei, S., Xu, B., Chen, Y., Yan, X., & Xia, H. (2015). Transparent organic materials of aircraft cockpit canopies: research status and development trends. *Materials Research Innovations*, 19(sup10), S10-199-S110-206. <https://doi.org/10.1179/1432891715Z.0000000002147>
- Weber, L. E. (1926). *The chemistry of rubber manufacture*: C. Griffin, limited.
- Yu, S., Li, J., Zhao, L., Gong, B., & Li, L. (2021). Folding-insensitive, flexible transparent conductive electrodes based on copper nanowires. *Solar Energy Materials and Solar Cells*, 231, 111323. <https://doi.org/10.1016/j.solmat.2021.111323>
- Yu, S., Li, L., Lyu, X., & Zhang, W. (2016). Preparation and investigation of nano-thick FTO/Ag/FTO multilayer transparent electrodes with high figure of merit. *Scientific reports*, 6(1), 20399. <https://doi.org/10.1038/srep20399>
- Yu, S., Liu, X., Wu, M., Dong, H., Wang, X., & Li, L. (2021). All-solution-processed molybdenum oxide-encapsulated silver nanowire flexible transparent conductors with improved conductivity and adhesion. *ACS Applied Materials & Interfaces*, 13(12), 14470-14478. <https://doi.org/10.1021/acsami.0c22324>
- Zilberberg, K., & Riedl, T. (2016). Metal-nanostructures—a modern and powerful platform to create transparent electrodes for thin-film photovoltaics. *Journal of Materials Chemistry A*, 4(38), 14481-14508. <https://doi.org/10.1039/C6TA05286J>

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KEY UNCERTAINTIES IN JIRA MEETINGS AND THEIR IMPLICATIONS FOR ORGANIZATIONAL STRUCTURING

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Abstract

This paper is an ethnographic analysis of Agile methodology (Jira) meetings at a large defense contracting company. Uncertainties expressed by engineers in the Jira status meetings promise to reveal important shifts in social structure and power.

Keywords: *Software Development; Agile Methodology; JIRA Technology; Coding Analysis.*

1. Introduction

Jira is a software tool that is primarily used by software developers but can also be used in any system development setting. It was launched in 2002 by two computer scientists in Australia (Jexo). It is commonly applied in Agile development environments because it supports the automation of the work flow that is otherwise handled manually or in an ad hoc (reactive) manner. Jira also incorporates elements from other applications such as Kanban but manages the workflow across these elements (Atlassian). Its name is said to derive from the Japanese word for Godzilla “Which makes sense because it goes hand in hand with squashing software bugs!” (Jexo)

Most research on Jira focuses on improvements in productivity (Al-Baik & Miller, 2014; Tanner & Dauane, 2017; Özkan & Mishra, 2019; Fisher & Ludwigsen, 2013; Patterson 2022). Although some research has leveraged convenient data sets available from the comments feature in Jira to analyze affect/sentiment amongst users (Valdez et. al., 2020; Ortu, et. al., 2015) or the degree to which new users accept the technology (Gorro et. al., 2019).

Still unexplored is an analysis of this new technology from a management and labor studies perspective. Labor studies, in general, shed light on the ways in which new technologies rearrange organizational structures (patterns on worker relationships) (Barley, 1996; Barley & Orr, 1997) as well as power dynamics across groups (Braverman, 1974; Bonjean & Grimes, 1970; Barley, 1996; Bovens & Zouridis, 2002; Burawoy, 1979; Burton & Van den Broek, 2009; Levina & Vaast, 2005; Rosen, 1984).

Interestingly, scholars have argued persuasively that organizational structures (patterned relations) grow in the direction key uncertainties in the organizational work itself (Stinchcombe, 1990). Therefore, this study will be centered on observation of the work activities (specifically, weekly Jira status meetings), to discern what uncertainties are foremost in the work activities. Once identified, these uncertainties will offer a theoretical vantage point from which to consider shifts in organizational structure.

2. Method

The author is a part-time engineer at a large defense contracting organization in New England. The organization is a professional bureaucracy with a matrix structure and, like most engineering

settings, has been migrating away from traditional system development life cycles toward rapid development methodologies such as Agile. The author was involved in a project for over a year before the Jira technology was introduced and has been involved with the Jira tool for over a year. Halfway through this period, the author moved from a hardware engineering group to a system engineering group, which offered a unique point of comparison for how each group adapted to the new technology.

The data gathered are qualitative (ethnographic) and are comprised of daily field-notes. Qualitative methodologies are applied to the data (coding) in order to find patterns and themes (Lofland & Lofland 1984; Spradley 1979; Strauss & Corbin 1990). The data were entered into a qualitative data analysis tool called Coding Analysis Toolkit (CAT). This toolkit captures ethnographic codes in the qualitative data and helps the analyst find patterns across them. When questions or inquiries occurred within the transcripts/notes, the author saw this as an indication of an area of uncertainty and the coding was largely linked to those instances.

3. Preliminary Analysis

The analysis is in its early stages. Patterns that are emerging include areas of uncertainty and the shifts they may be compelling in organizational structure.

3.1. Work to be Completed

A major feature of Jira is periodic Program Increment (PI) planning. This occurs every couple of months and defines tasking to a much greater granularity than non-Agile methods do. Once the PI planning is complete, bi-weekly (twice per week) Jira status meetings are held and migrate tasks across different levels of completion. This includes moving tasks from inactive status to active, as well as moving completed tasks to review and complete statuses. It also removes uncertainty over what a particular engineer's tasking is at any given time, meaning that the engineer has less potential to abuse slack times that naturally occur when superiors and coworkers have imperfect knowledge of one's actual productivity.

Structurally, Jira PI planning meetings are a response to this uncertainty. In traditional development life cycles, task definition is more top-down and hierarchical with more senior engineers and managers performing this task with relatively little input from the eventual task owners. Therefore, this reflects a shift toward a more communal approach to task definition that directly includes those who will be performing the work. In parallel with these positive structural changes, however, is the relative diminishing of the potential for workers to abuse slack times that result from imperfect knowledge over one's task progress.

3.2. The Jira Point System (Fibonacci Sequence)

The Fibonacci sequence is a series of numbers that represent the sum of the numbers prior. Therefore, it involves the integers 0, 1, 2, 3, 5, 8, 13, 21, etc. These numbers are intended to reflect the level of effort for a particular task based on complexity and overall duration. Especially early on, the engineers expressed high levels of uncertainty regarding the number to assign to a particular task. This is compounded by the fact that the number does not map onto other measures of level-of-effort (LOE) such as hours or dollars. Rather, it serves to provide a relative indication of task effort for PI planning purposes. Nonetheless, a lot of discussion revolves around examining a task to determine what Fibonacci integer to use.

From a structural point of view, it is clear that a subset of the Jira meetings activities described above also entail a deeper examination of the complexity and volume of work tasks. In the team

environment, all team members are present and have a voice in these evaluations as well as the potential to learn what tasks are being performed by others. This represents a shift from more traditional development methodologies fostering improved information sharing and learning.

3.3. How To Present Jira Status to The Customer

One of the selling points of Jira to organizations is that they can promise more transparency and task completion status to their customers. Various reports can be generated that illustrate this progress graphically. Engineers are highly sensitive to how these reports are developing and will often redefine work throughout the PI to ensure that the reports show a predictable and reliable level of task completion through time. In some cases, defined tasks will be reallocated to the next program increment to achieve this goal, or to address lateness in task completion.

Therefore, this uncertainty influences the relationship between the producers of the product and the customer paying for production. While on the one hand Jira claims a more transparent and granular presentation of status/progress to the customer, on the other hand, the Jira tool and process includes flexibility and slack enabling a more favorable narrative to the customer. Together these shifts encourage a tighter and more positive structure between the producer and the customer even though they have the potential to hide errors in the work forecasting.

3.4. How to Properly Use the Jira Tool

The Jira tool provides a means for tasks to be defined, LOE identified, migration of tasks from start to completion, as well as a feature that allows the task owner and reviewers to make comments on the task and auto-generate an email to the task own when a comment is entered. Furthermore, depending upon the program and its unique needs, additional attributes are created for each task enabling project managers to more easily track status and issues. While some team members are the Jira administrators and handle most of these uncertainties, nevertheless a good deal of dialogue during the status meetings centers on simply how to use the tool properly.

3.5. Managing Commitments Across Programs

The setting under study is a matrix structure in which managers oversee groups of engineers dedicated to a particular function such as software engineering, hardware engineering or systems engineering. Each engineer then gets allocated to tasking associated with particular programs (contracts). Therefore, many engineers charge their time to more than one program and this becomes a factor at the Jira meetings when resource planning is occurring.

To address these uncertainties, engineers take on or cede work responsibilities to better even out the overall tasking loads. Compared to traditional development life cycle practice, this represents a shift in which the worker themselves coordinate the task loading amongst themselves leading to a more amiable solution.

3.6. Differences Between the Hardware and Systems Engineering Groups

As mentioned earlier, Jira requires that tasks be defined at a finer granularity than with traditional methods. The primary difference between the hardware and the systems groups are reflected in the work artifacts and their representation in documentation. The hardware artifacts were primarily circuit diagrams, signal listings, Interface Control Drawings (ICDs), and spreadsheets. These kinds of work products lent themselves to being defined as Jira tasks mostly on a one-to-one basis – that is, each product was generally a whole Jira task. Conversely, with the systems engineering group, the work products were primarily requirements specifications. In the system development lifecycle (whether traditional or agile), requirements are highly scrutinized

because they precede design phases and if they are not defined well, fixing errors in subsequent phases becomes exponentially costly. Therefore, when defining Jira tasking for the requirements specifications, it was common to assign a specific number of requirements (typically twenty-five), to be the task for development and review.

The uncertainty of how to carve up larger work tasks into ones to be managed in the Jira tool differs across these groups. While this may not have any direct effect on organizational structure, it is clear that the nature of the work differs across these groups and influences how they decompose the tasking.

4. Summary

Table 1 provides a summary capture of the key themes and implications of this analysis.

Table 1. Summary of Themes and Structural Implications of the Analysis

Theme	Structural Implications
Work to be completed	More communal approach to task definition
The Jira point system (Fibonacci sequence)	More task analysis and information sharing
How to present Jira status to the customer	Ability to make adjustments to performance metrics that improve producer/customer relations
How to properly use the Jira tool	Implications for training and need for improved communications between administrators and non-administrators
Managing commitments across programs	Shift away from SDLC in which the workers have more responsibility in balancing workloads across programs
Differences between the hardware and systems engineering groups	Recognition that tasking is defined differently across functional areas and this has implications for the task granularity and form in the Jira tool

Over 70% of companies utilize Agile methods worldwide (Appfire (2024) Simform (2022)). Therefore, as more and more organizations are adopting Jira to automate the Agile activities, the findings in this study should be useful to most organization in terms of understand the social and structural changes they may experience. Although in its early stages, the analysis promises to provide insights to both practitioners and organizational theorists regarding adaptations of organizational structures to areas deemed by the workers to be both important and uncertain. As seen in the analysis, these shifts center on a move away from a traditional top-down allocation of work to subordinates fostering more participation by the workers themselves and a great deal more information sharing amongst them. This leads to a shift in which the team as a whole has more knowledge about the work and the work activities which has the potential to empower all

while at the same time diminishing the potential for a worker to abuse imperfect knowledge about work tasking by enjoying slack times.

These findings should also be relevant to labor scholar theorists seeking to understand shifts in power and control that occur when new technologies are introduced ((Braverman, 1974; Bonjean & Grimes, 1970; Bovens & Zouridis, 2002; Burawoy, 1979; Burton & Van den Broek, 2009; Levina & Vaast, 2005; Rosen, 1984). In particular, the increase in visibility of the worker's tasking to coworkers and superiors represents the potential for increased control. Indeed, Foucault's analysis of Bentham's "Panopticon" metaphor as an institutional structure comes to mind, but with the twist that adjacent cells have visibility to one another (Foucault, 1977). Is this a new way for organizations to obtain more control by having the workers control each other?

In conclusion, while the analysis needs to be refined and deepened, the preliminary results show promise to shed light on shifts in power and structure introduced by a new technology such as Jira that is becoming increasingly adopted by professional bureaucracies that should be of interest to practitioners and organizational scholars.

5. Disclaimer Statements

Funding: None

Conflict of Interest: None

6. References

- Al-Baik, O., & Miller, J. (2014). The kanban approach, between agility and leanness: a systematic review. *Empirical Software Engineering*, 20(6), 1861–1897. <http://doi.org/10.1007/s10664-014-9340-x>
- Appfire (2024). The who, what and where of Agile transformation today
<https://appfire.com/resources/blog/who-what-where-of-agile-transformation>
- Atlassian <https://www.atlassian.com/agile/kanban>
- Barley, S. R. (1996). Technicians in the Workplace: Ethnographic Evidence for Bringing Work into Organization Studies. *Administrative Science Quarterly*, 41: 404-441.
- Barley, S. R. & Orr, J. E. (eds.) (1997). *Between Craft and Science: Technical Work in U.S. Settings*. ILR Press: Ithaca.
- Braverman, H. (1974). *Labor and monopoly capital*. New York: Monthly Review Press.
- Bonjean, C. M. & Grimes, M. D. (1970). Bureaucracy and alienation: a dimensional approach. *Social forces*. March, Vol. 48, Issue 3, pp. 365-373. <https://doi.org/10.2307/2574655>
- Bovens, M. & Zouridis, S. (2002). From street-level to system-level bureaucracies: how information and communication technology is transforming administrative discretion and constitutional control. *Public administration review* 62(2), 174-184. <https://www.jstor.org/stable/3109901>
- Burawoy, M. (1979). *Manufacturing consent*. Chicago: The University of Chicago Press.
- Burton, J. & Van den Broek, D. (2009). Accountable and countable: Information management systems and the bureaucratization of social work. *British journal of social work* 39(7), 1326-1342
<http://dx.doi.org/bcn027>
- Fisher, J., Koning, D., & Ludwigsen, A. P. (2013). *Utilizing Atlassian JIRA for large-scale software development management* (No. LLNL-CONF-644176). Lawrence Livermore National Lab.(LLNL), Livermore, CA (United States).
- Foucault, M. (1977). *Discipline & Punish: The Birth of the Prison*. Vintage Books, New York.
- Gogoll, J., Zuber, N., Kacianka, S., Greger, T., Pretschner, A., & Nida-Rümelin, J. (2021). Ethics in the software development process: from codes of conduct to ethical deliberation. *Philosophy & Technology*, 1-24.
- Gorro, K., Ilano, A., Sebial, A., Ranolo, E., & Vale, E. (2019). Qualitative Technology Acceptance Evaluation of JIRA in Software Development Using Machine Learning.

- Heidegger, M. (1977). The question concerning technology. *In the question concerning technology and other essays*. Harper & Row Publishers.
- Ihde, D. (2010). *Heidegger's technologies: postphenomenological perspectives*. Fordham University Press, New York (2010).
- Jexo <https://jexo.io/blog/atlassian-jira-history/>
- Mitcham, C. (2022). *Thinking through technology: The path between engineering and philosophy*. University of Chicago Press.
- Levina, N. & Vaast, E. (2005). The emergence of boundary spanning competence in practice: implications for implementation and use of information systems. *Management information systems quarterly* 335-363. <https://doi.org/10.2307/25148682>
- Lofland, J and Lofland L H (1984) *Analyzing Social Settings*. Wadsworth Inc.
- Ortu, M., Adams, B., Destefanis, G., Tourani, P., Marchesi, M., & Tonelli, R. (2015, May). Are bullies more productive? Empirical study of affectiveness vs. issue fixing time. In *2015 IEEE/ACM 12th Working Conference on Mining Software Repositories* (pp. 303-313). IEEE. doi: [10.1109/MSR.2015.35](https://doi.org/10.1109/MSR.2015.35).
- Özkan, D., & Mishra, A. (2019). Agile Project Management Tools: A Brief Comparative View. *Cybernetics and Information Technologies*, 19(4), 17-25. doi:[10.2478/cait-2019-0033](https://doi.org/10.2478/cait-2019-0033)
- Patterson, A. M. (2022). *Evaluation of Jira Software Adoption Strategies at a Large Technology Company*. Wilmington University (Delaware).
- Rosen, M. (1984). Power and culture in bureaucracy: a study of bureaucracy as a control mechanism in monopoly capitalism. Ph.D. dissertation, University of Pennsylvania.
- Simform (2022). Agile Adoption Statistics: How is Software Development changing? Looking to choose agile over other traditional methodologies? Here is the state of agile adoption to understand why you need it the most!
<https://www.simform.com/blog/state-of-agile-adoption/#:~:text=Agile%20adoption%20has%20increased%20over,improved%20software%20quality%20with%20agile.>
- Stinchcombe, A. (1990). *Information and Organizations*. University of California Press.
- Strauss A & Corbin J (1990) *Basics of Qualitative Research: Grounded Theory Procedures and Techniques*. Sage Publications.
- Tanner, M. and Dauane, M. (2017). The Use of Kanban to Alleviate Collaboration and Communication Challenges of Global Software Development, *Issues in Informing Science + Information Technology*, Vol. 14
- Valdez, A., Oktaba, H., Gómez, H., & Vizcaíno, A. (2020, November). Sentiment analysis in jira software repositories. In *2020 8th International Conference in Software Engineering Research and Innovation (CONISOFT)* (pp. 254-259). IEEE. doi: [10.1109/CONISOFT50191.2020.00043](https://doi.org/10.1109/CONISOFT50191.2020.00043).

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ECONOMIC EVALUATION OF AN ELECTROMECHANICAL FACILITY

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Abstract

This study provides a structured framework through the integration of INCOSE's risk management process with the financial valuation ratios from CFI to evaluate the viability of an electromechanical startup from a financial perspective. This study uses the three-statement financial model to show how risk-informed decision making improves profitability within a quarterly timeline in the first year while simultaneously stabilizing leverage and efficiency ratios. The findings show that combining systems engineering risk management with financial modeling improves cost efficiency, schedule adherence, and economic sustainability, while aligning with KEEN's "create value" principle.

Keywords: *Entrepreneurial Mindset; Project-Based Learning; Financial Decision-Making; Engineering Education; KEEN; System Engineering; Risk Management; INCOSE.*

1. Introduction

The demand for high-quality electromechanical parts without the high cost associated with them has been increasing at an alarming rate. Low-cost and high-quality electromechanical parts are particularly needed in the aerospace, automotive, telecommunications, and defense industries. The key factor driving up the cost of these components is the high customization and uniqueness of the part that is required for the industries.

To validate and verify the economic viability of a startup, a holistic and lifecycle-based approach that considers the technical, financial, and strategic aspects needs to be adopted to understand the valuation of the startup. Traditional financial models do not account for the associated risks, uncertainties, and performance trade-offs, therefore creating a need to implement a system engineering perspective in addition to the discounted cash flow models and earning multipliers from the traditional financial assessment methodology.

The decision-making process is guided by risk-informed trade studies from the system engineering domain, thus balancing the economic feasibility of the startup and lifecycle cost modeling, tracing back to the stakeholder needs via system requirements. A risk management framework was adopted from the INCOSE handbook, providing a structured approach to identify, assess, and mitigate risks across the system development lifecycle.

This integration between financial valuation in the form of financial metrics and valuation ratios from CFI as well as the technical risk perspective aligns with the create value principle from KEEN, placing a high importance on opportunity recognition, iterative innovation, and economic sustainability. This study integrates INCOSE's risk management framework, CFI's valuation methodologies, and KEEN's create value principle to provide a structured approach for assessing profitability, leverage, liquidity, and efficiency to guarantee that the valuation methodology is data-

driven, iterative, and lifecycle compliant.

2. The Kern Entrepreneurial Engineering Network (KEEN)

The KEEN initiative, key to modern engineering education transformation, is focused on the 3Cs of the entrepreneurial mindset: connections, curiosity, and creating value (Lynch A.C. et al, 2024). Although these three principles are important and discussed in this paper, emphasis will be placed on the creating value principle for the purpose of this study.

Within the context of the KEEN framework, the curiosity principle provides students and engineers with the capability to not only question traditional methodologies but also foster a mindset of continuous learning through the constant search for opportunities and alternative solutions to current problems (Curiosity, n.d.). Within the context of the KEEN framework, the connection principle is that students and engineers alike can work together to create collaboration between industry and academia. This collaboration results in the transfer of knowledge through a collaborative environment, fostering a community with an entrepreneurship mindset (Bosman. L, et. al, 2017).

Within the context of the KEEN framework and the focus of this study, the creating value principle highlights the importance of having a positive impact on both individuals and society by solving pressing problems (CREATING VALUE, n.d.). This principle fosters effective communication between stakeholders and engineers, allowing them to receive and understand the vision conveyed to them. This vision consists of defined and structured milestones and goals extending beyond product innovation to include a value-focused mindset driven by stakeholder requirements (CREATING VALUE, n.d.). Ingrained with this principle, engineers now broaden their perspectives to provide valuable and effective solutions to meet customer requirements and address societal needs in the process (CREATING VALUE, n.d.).

3. International Council on Systems Engineering (INCOSE)

During the development of any system, risk is a fundamental factor for both engineering and financial aspects and is exacerbated when the complexity of the system increases. According to INCOSE, risk is defined as the combined probability of an event occurring that will have an impact on cost, performance, and schedule (Walden, et al., 2023). To proactively mitigate the impact on system cost, performance, and schedule, INCOSE provided an iterative structured framework to identify, assess, handle, monitor, and control risks and uncertainties, guaranteeing that the risks are addressed early in the development lifecycle (Walden, et al., 2023).

Risk identification, defined by INCOSE, is the systematic process of discovering failures, uncertainties, and external dependencies that could potentially affect the cost, performance, and schedule of the system. The identified risk was then analyzed and prioritized using qualitative and quantitative methods to understand, determine, and rank the likelihood, impact, and detectability of the identified risk. Risks are eliminated or reduced in one of four ways: mitigation, avoidance, transfer, or acceptance. The risks are then monitored and controlled by treating them as a dynamic entity within the system that will fluctuate depending on the complexity of the system and the influence of external variables on the system (Walden, et al., 2023).

4. Corporate of Finance Institute (CFI)

During the investment decision-making process, the financial valuation methodology by CFI presents itself as a structured framework to determine a firm's financial health, operational efficiency, and attractiveness. This financial valuation framework efficiently categorizes financial

metrics into four ratios, as part of the financial ratio analysis. These ratios are profitability ratios, leverage ratios, efficiency ratios, and liquidity ratios. These ratios provide the necessary information for making sound investment decisions for both public and private practices (Financial Ratios ebook, n.d.).

Profitability ratios use return on assets (ROA), return on equity (ROE), and net profit margin to gauge the ability of the firm to generate profit respective to its revenue, balance sheet assets, operating costs, and shareholder equity during a point in time. Leverage ratios use the debt-to-equity (D/E) ratio and equity ratio to gauge the financial risk and stability of the capital structure, directly influencing the valuation capital cost and financial resilience of the firm. Efficiency ratios use the asset turnover ratio and inventory turnover ratio to gauge and determine the resource utilization and production process efficiency of the firm to maximize cash flow. The liquidity ratio uses the current and quick ratios to gauge a firm's ability to meet short-term liabilities during a financial distress situation within the prediction model. The liquidity ratio correlates with a firm's resilience during unforeseen economic turmoil and market fluctuations out of the norm (Financial Ratios ebook, n.d.).

5. Problem Statement

This study evaluates an electromechanical manufacturing startup using the INCOSE risk management framework integrated with CFI financial valuation to gauge the financial impact on cost, performance, and schedule aligning with KEEN by creating value for the customer and overall technological reliability within the industry.

6. Research Questions (RQ)

This study is guided by the following research questions (RQs):

RQ1: Can the risk management framework positively impact performance?

RQ2: Can the risk management framework positively impact on costs associated with production?

RQ3: Can the risk management-based schedule have a positive financial impact?

7. Methodology

7.1. Risk Identification

The risk identification process involves identifying risks that have the potential to negatively impact the startup's long-term sustainability. Risks are then classified into technical, financial, operational, and market risks, with each directly impacting valuation metrics (Walden, et al., 2023). The asset turnover ratio and inventory turnover ratio assess the technical risk. The debt-to-equity, current, and quick ratios assess a firm's financial risk. The operating profit margin and the return on capital employed assess the operational risk of the firm. The price-to-earnings ratio and EV/EBITDA ratio assess the market risk impacting revenue generation. Valuation metrics integrated with risks create a multidimensional risk identification process to quantify the vulnerabilities (Walden, et al., 2023).

7.2. Risk Analysis

The probability and impact of the risks were analyzed using probabilistic risk assessment and sensitivity analysis to study the uncertainty of the risk and its impact on the cost, schedule, and performance of the firm. Profitability ratios assess a firm's financial resilience. The leverage ratios were tested for variations. The efficiency ratios were assessed for production bottlenecks. The

liquidity ratio assesses the financial liquidity risk. Trade-space analysis provides risk-adjusted valuation projection.

7.3. Risk Treatment

Strategies are put in place to mitigate, avoid, transfer, or accept risks to guarantee the resilience of the firm under financial uncertainty, which includes but is not limited to technical uncertainties, environmental uncertainty that impacts operations, and government policy uncertainty that trickles operations and financial impact. Mitigating risks involves cost control. Avoidance risk involves process optimization. Risk transfer involves the use of insurance policies to transfer risks. Accepting risk involves accepting that certain risks are within the acceptable range but closely monitored for their potential impact on the firm.

7.4. Risk Monitoring and Control

Risk control measures are used to monitor risk throughout the firm's lifecycle. Financial risk dashboards use financial ratios as key performance indicators that allow real-time monitoring. A range limit is set to create an automated alert using the four ratios as the key risk indicators. This allows the technical and financial risks to be managed in a dynamic manner, guaranteeing the financial and operational viability of the firm through the entire lifecycle.

8. Results

The results presented in this section were derived from a hypothetical three-statement financial model created by the authors in Microsoft Excel. The model simulates the operations of an electromechanical manufacturing facility during its first year based on the cost structures and valuation ratios outlined in CFI's financial analysis framework (Stankevičienė J., et al., 2011). These results are not from an existing company, but from projected assumptions to demonstrate the application of the proposed methodology (Labunska S. V. et al., 2018) (Ravid S. A., et al., 1997).

8.1. Income Statement

The income statement in figure 1 shows that the firm incurs high initial operating losses during the first quarter and slowly recovers during the second quarter and onwards. This is because of the high startup costs and limited production output. During the fourth quarter, profitability emerges as revenue from scaled operations surpasses the fixed overhead costs.

		Y1				Y2	Y3	Y4	Y5
		Q1	Q2	Q3	Q4				
		\$	\$	\$	\$	\$	\$	\$	\$
Revenue	Income	0.00	65,700.00	82,125.00	109,500.00	115,632.00	122,107.39	128,945.41	136,166.35
	Total Revenue	0.00	65,700.00	82,125.00	109,500.00	115,632.00	122,107.39	128,945.41	136,166.35
Cost of Goods Sold Including D&A	Inventory	65,700.00	65,700.00	65,700.00	65,700.00	69,379.20	73,264.44	77,367.24	81,699.81
	Labor	11,440.00	11,440.00	11,440.00	11,440.00	12,080.64	12,757.16	13,471.56	14,225.96
	Overhead	10,000.00	10,000.00	10,000.00	10,000.00	10,560.00	11,151.36	11,775.84	12,435.28
	Total COGS	87,140.00	87,140.00	87,140.00	87,140.00	92,019.84	97,172.95	102,614.64	108,361.06
	Total Gross Profit	(87,140.00)	(21,440.00)	(5,015.00)	22,360.00	23,612.16	24,934.44	26,330.77	27,805.29
Expense	Operating	3,000.00	3,000.00	3,000.00	3,000.00	3,168.00	3,345.41	3,532.75	3,730.58
	Marketing & Sales	1,000.00	1,000.00	1,000.00	1,000.00	1,056.00	1,115.14	1,177.58	1,243.53
	Admin	1,000.00	1,000.00	1,000.00	1,000.00	1,056.00	1,115.14	1,177.58	1,243.53
	Insurance	1,000.00	1,000.00	1,000.00	1,000.00	1,056.00	1,115.14	1,177.58	1,243.53
	Software	1,095.00	1,095.00	1,095.00	1,095.00	1,156.32	1,221.07	1,289.45	1,361.66
	Holding	7,095.00	7,095.00	7,095.00	7,095.00	7,492.32	7,911.89	8,354.96	8,822.83
	Total OPEX	(94,235.00)	(28,535.00)	(12,110.00)	15,265.00	84,527.52	89,261.06	94,259.68	99,538.22
EBITDA									
Depreciation	Printers	5,000.00	5,000.00	5,000.00	5,000.00	5,280.00	5,575.68	5,887.92	6,217.64
EBIT		(99,235.00)	(33,535.00)	(17,110.00)	10,265.00	79,247.52	83,685.38	88,371.76	93,320.58
Interest	Expense	1,000.00	1,000.00	1,000.00	1,000.00	1,056.00	1,115.14	1,177.58	1,243.53
EBT		(100,235.00)	(34,535.00)	(18,110.00)	9,265.00	78,191.52	82,570.25	87,194.18	92,077.05
Taxes	Federal (21%)	(21,049.35)	(7,252.35)	(3,803.10)	1,945.65	2,054.61	2,169.66	2,291.17	2,419.47
	State (7%)	(7,016.45)	(2,417.45)	(1,267.70)	648.55	684.87	723.22	763.72	806.49
	Total Tax	(28,065.80)	(9,669.80)	(5,070.80)	2,594.20	2,739.48	2,892.89	3,054.89	3,225.96
	Net Income	(72,169.20)	(24,865.20)	(13,039.20)	6,670.80	75,452.04	79,677.36	84,139.29	88,851.09

Figure 1. Income Statement

8.2. Balance Sheet

The balance sheet in figure 2 shows a steady improvement in equity position as retained earnings increase from the fourth quarter onwards. The cash and cash equivalent shows that the firm bleeds cash in the first three quarters of the first year but recovers within the fourth quarter of the first year.

		Y1				Y2	Y3	Y4	Y5
		Q1	Q2	Q3	Q4				
		\$	\$	\$	\$	\$	\$	\$	\$
Asset	Current	(72,169.20)	(24,865.20)	(13,039.20)	6,670.80	75,452.04	79,677.36	84,139.29	88,851.09
	Cash & Cash Equivalents								
	Accounts Receivable	0.00	9,855.00	12,318.75	16,425.00	17,344.80	18,316.11	19,341.81	20,424.95
	Inventory	21,878.10	21,878.10	21,878.10	21,878.10	23,103.27	24,397.06	25,763.29	27,206.04
	Total Current Assets	(50,291.10)	6,867.90	21,157.65	44,973.90	115,900.12	122,390.53	129,244.39	136,482.08
Non-Current	Fixed Asset	10,000.00	10,000.00	10,000.00	10,000.00	40,000.00	40,000.00	40,000.00	40,000.00
	Property & Plant								
	Accumulated Depreciation	(500.00)	(1,000.00)	(1,500.00)	(2,000.00)	(4,000.00)	(6,000.00)	(8,000.00)	(10,000.00)
	Net Property & Plant	9,500.00	9,000.00	8,500.00	8,000.00	36,000.00	34,000.00	32,000.00	30,000.00
	Equipment	7,250.00	7,250.00	7,250.00	7,250.00	29,000.00	29,000.00	29,000.00	29,000.00
	Accumulated Depreciation	(500.00)	(1,000.00)	(1,500.00)	(2,000.00)	(4,000.00)	(6,000.00)	(8,000.00)	(10,000.00)
	Net Equipment	6,750.00	6,250.00	5,750.00	5,250.00	25,000.00	23,000.00	21,000.00	19,000.00
	Total Non-Current Asset	16,250.00	15,250.00	14,250.00	13,250.00	61,000.00	57,000.00	53,000.00	49,000.00
	Total Asset	(34,041.10)	22,117.90	35,407.65	58,223.90	176,900.12	179,390.53	182,244.39	185,482.08
Liabilities	Current	29,046.67	29,046.67	29,046.67	29,046.67	7,668.32	8,097.75	8,551.22	9,030.09
	Accounts Payable								
	Total Current Liabilities	29,046.67	29,046.67	29,046.67	29,046.67	7,668.32	8,097.75	8,551.22	9,030.09
	Long-Term Debt	50,000.00	50,000.00	50,000.00	50,000.00	50,000.00	50,000.00	50,000.00	50,000.00
	Total Non-Current Liabilities	50,000.00	50,000.00	50,000.00	50,000.00	50,000.00	50,000.00	50,000.00	50,000.00
Equity	Total Liabilities	79,046.67	79,046.67	79,046.67	79,046.67	57,668.32	58,097.75	58,551.22	59,030.09
	Owners Capital								
	Retained Earnings	40,000.00	40,000.00	40,000.00	40,000.00	40,000.00	40,000.00	40,000.00	40,000.00
	Total Equity	(73,264.20)	(99,224.40)	(113,358.60)	(107,782.80)	(33,425.76)	45,156.60	128,200.90	215,956.99
		(33,264.20)	(59,224.40)	(73,358.60)	(67,782.80)	6,574.24	85,156.60	168,200.90	255,956.99

Figure 2. Balance Sheet

8.3. Cashflow Statement

The cash flow statement in figure 3 shows that the operating cash flow is negative during the first three quarters and positive in the fourth quarter, reflecting improved working capital management. Cash inflows from operations offset early capital expenditures, thus stabilizing liquidity by the year-end.

	Y1				Y2	Y3	Y4	Y5
	Q1	Q2	Q3	Q4				
	\$	\$	\$	\$	\$	\$	\$	\$
Net Income	(72,169.20)	(24,865.20)	(13,039.20)	6,670.80	75,452.04	79,677.36	84,139.29	88,851.09
Depreciation, Depletion & Amortization	1,000.00	1,000.00	1,000.00	1,000.00	4,000.00	4,000.00	4,000.00	4,000.00
Net Cash from Operating Activities	(71,169.20)	(23,865.20)	(12,039.20)	7,670.80	79,452.04	83,677.36	88,139.29	92,851.09
Deferred Taxes								
Funds from Operation	50,000.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
Working Capital Changes	40,000.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
Net Cash from Financing Activities	90,000.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
Net Change in Cash	18,830.80	(23,865.20)	(12,039.20)	7,670.80	79,452.04	83,677.36	88,139.29	92,851.09

Figure 3. Cashflow Statement

8.4. Ratios

The ratios shown in figure 4, 5, 6, 7, and 8 are a detailed breakdown of metrics outlined in the CFI to determine the financial health of the company on specific aspects. These numbers were obtained from the above three-statement financial model to provide different perspectives to the firm, such as financial risk, production capacity, loan obligations, and the ability of the firm to turn a profit.

		Y1	Y2	Y3	Y4	Y5
Return On Equity	Uses bottom line to gauge profitability					
Return On Assets	Capital Invested in Assets are used gauge profitability					
Return On Capital Employed	Measures efficiency in profit generation based on Capital Utilization					
Gross Margin Ratio	Indicate profitability after COGS expenses					
Operating Profit margin	Ratio based on the operation by total revenue					
Net Profit Margin	Net profit per dollar revenue gained					

Figure 4. Profitability Ratios

		Y1	Y2	Y3	Y4	Y5
Debt-to-Equity Ratio	Compares total debt and liability to Shareholder Equity					
Equity Ratio	Indicates Residual claim of Shareholders on a business					
Debt Ratio	Indicates percentage of assets financed with debt (How Solvent is the company)					

Figure 5. Leverage Ratios

		Y1	Y2	Y3	Y4	Y5
Accounts Receivable Turnover Ratio	Indicates how many times a company collects its account receivable over a period of time					
Accounts Receivable Days	Indicates how many days taken to collect on credit sales from customers					
Asset Turnover Ratio	Efficiency in Sales Generation using company assets					
Inventory Turnover Ratio	Indicate how many times stock of Good are Sold and Restocked					
Inventory Turnover Days	Measures Business efficiency, how long it takes to sale a stock of inventory					

Figure 6. Efficiency Ratios

		Y1	Y2	Y3	Y4	Y5
Assets Ratios						
Current Ratio	Measures ability to meet short-term Obligations due in one year					
	Measures ability to pay short-term liabilities using readily convertible cash	0.07	15.11	15.11	15.11	15.11
	Measures ability to pay short-term liabilities using cash and cash equivalents	-0.56	12.10	12.10	12.10	12.10
	Days of operation before a business needs to tap into capital sources aside its current assets	-0.89	9.84	9.84	9.84	9.84
Defensive Interval Ratio		0.94	104.78	104.78	104.78	104.78
Earnings Ratio						
Times Interest Earned Ratio						
Cash Flow Ratio	Ability to meet debt obligations on a periodic basis	-34.90	75.05	75.05	75.05	75.05
	Ability to meet debt obligations on a periodic basis based on cash on hand					
Times Interest Earned Ratio (Cash Basis Ratio)						
CAPEX to Operating Cash Ratio	Quantifies how much of company cash flow is channeled its into growth.	-33.90	78.83	78.63	78.44	78.26
	Determines if a business can generate cash flow from its core business to pay off its current liabilities	-0.59	0.77	0.68	0.60	0.53
Operating Cash Flow Ratio		-0.86	10.36	10.33	10.31	10.28

Figure 7. Liquidity Ratios

Price Ratios		Y1	Y2	Y3	Y4	Y5
Price-to-Earnings Ratio	Compares the relative value of different companies	Share Price / Earnings per Share	5.00	5.00	5.00	5.00
Enterprise Value Ratios						
EV/EBITDA Ratio	Compares the relative value of different companies post Interest, tax Depreciation and Amortization	(Market Capitalization + Net Debt) / EBITDA	1.37	4.16	4.13	4.10
EV/EBIT Ratio	Compares the relative value of different companies while considering Earnings post Interest and tax only	(Market Capitalization + Net Debt) / EBIT	1.17	4.44	4.41	4.37
EV/Revenue Ratio	Compares the relative value of different companies while considering Revenue only	(Market Capitalization) / Revenue	4.16	3.26	3.26	3.26

Figure 8. Multiple Valuation Ratios

9. Discussion

9.1. Addressing Research Questions

The aspect of performance raised in the first research question shows that the framework improved operational performance by reducing variability in production schedules. The income statements show the profitability achieved in the fourth quarter. This aligns with reduced risk exposure in production and supply chain activities. Efficiency ratios further confirm that the improved throughput as risks was mitigated in a structured manner early on, in addition to the upward trends in the multiple valuation ratios.

The cost brought up in the second research question is addressed in the implementation of risk-informed planning that allows for a three-shift production schedule with minimal supervisory overhead due to the high volume of mechanized processes throughout the facility. This lowered the direct labor cost, as shown in the income statement, by reducing the overhead per unit. Cost savings are directly observable in terms of the ratios, specifically profitability and efficiency ratios.

The financial impact on scheduling in the third research question was addressed in the sense that risk management facilitates predictable scheduling. This allows the firm to scale its production to 150 parts per day. This accelerated delivery improved customer payments and stabilized revenue flow, as is evident from the positive shift in operating cash flow and net profit margin.

9.2. Implications & Limitations

Implications of the systems engineering approach to valuation and KEEN's create value principle in academia pedagogy and research close the gap between engineering risk management and financial modeling, fostering an environment for interdisciplinary collaboration. This opens research on lifecycle cost analysis, systems-based financial decision-making, and structured risk-informed investment models.

The implications of this framework for government agencies allow government agencies to leverage this framework to secure policies involving innovation grants, technology transfer programs, and manufacturing initiatives. The evidence-based decision-making involved in this framework provides a structured approach for refining the financial disclosure requirements for emerging technology ventures.

The implications of this framework are beneficial to the industry for assessing capital-intensive startups. A more informed investment decision can be made by integrating the risk-management framework and financial ratios. This also improves financial forecasting and resource allocation for a given firm, as a risk-adjusted forecasting model can be implemented to optimize the capital structure.

The model relies on projected assumptions that may introduce optimism bias (Sharot, 2011). Real-world data may vary due to market volatility, supply chain disruption, or unmodeled risks such as earthquakes, pandemics, and financial crises.

10. Conclusion

Integrating INCOSE's risk management framework with CFI financial valuation provides a structured data-driven approach for assessing the economic viability of an electromechanical startup. The findings demonstrate that risk-informed decision making enhances profitability, improves scheduling adherence, and reduces financial ambiguity.

11. Disclaimer Statements

Funding: None

Conflict of Interest: None

12. References

- Lynch, A. C., Cupertino, P. C. P., Chikwendu, D. I., Subramaniam, S., & Alagiri, S. (2024). Building connections: Discovering the entrepreneurial mindset by creating a three statement financial model. Industry, Engineering & Conference Management Systems Conference.
- Curiosity: What do we mean? (n.d.). Engineering Unleashed.
<https://engineeringunleashed.com/card/1493>.
- Bosman, L., Mayer, B., & McNamara, P. J. (2017). Curriculum Innovation: Incorporating the Kern Engineering Entrepreneurial Network (KEEN) Framework into Online Discussions. In *Proceedings of the 120th ASEE Annual Conference & Exposition*. American Society for Engineering Education.
- CREATING VALUE: A component of entrepreneurial mindset (n.d.). Engineering Unleashed
<https://engineeringunleashed.com/creating-value>
- Walden, D. D., Shortell, T. M., Roedler, G. J., Delicado, B. A., Mornas, O., Yip, Y. S., & Endler, D. (Eds.). (2023). INCOSE systems engineering handbook (5th ed.). John Wiley & Sons Ltd.
- Financial ratios ebook. (n.d.). <https://corporatefinanceinstitute.com/assets/CFI-Financial-Ratios-Cheat-Sheet-eBook.pdf>
- Labunska, S. V., Prokopishyna, O. V., & Iermachenko, I. V. (2018). Cognitive modeling of the startup life cycle. *Проблеми економіки*, (2), 214-220.
- Stankevičienė, J., & Žinytė, S. (2011). Valuation model of new start-up companies: Lithuanian case. *Business: Theory and Practice*, 12(4), 379-389.
- Ravid, S. A., & Spiegel, M. (1997). Optimal financial contracts for a start-up with unlimited operating discretion. *Journal of Financial and Quantitative Analysis*, 32(3), 269-286.
- Sharot, T. (2011). The optimism bias. *Current biology*, 21(23), R941-R945.

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IMPROVING POST-SALE SUPPORT AND CUSTOMER SATISFACTION WITH ADDITIVE MANUFACTURING

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Abstract

This study investigates the potential of additive manufacturing (AM) to transform post sale services by enabling on-demand spare parts production, thereby reducing repair lead times and inventory costs. The research examines the inherent challenge of conventional manufacturing methods. It evaluates AM's potential to address these challenges while introducing new operational considerations. Qualitative case studies are incorporated to further illustrate the improvements in service quality and the challenges encountered during AM integration.

Keywords: *3D Printing; Additive Manufacturing; Spare Parts; Supply Chain; Customer Satisfaction.*

1. Introduction

In today's competitive global market, customer satisfaction is very important to long-term business success. Post-sale service is a critical part of the product lifecycle, encompassing maintenance, repairs, and providing spare parts to customers long after the initial sale. High-quality customer service in the post-sale phase is increasingly recognized as a critical driver of customer satisfaction and brand loyalty. Research indicates that enhancements in service quality can significantly boost customer satisfaction and repurchase probability (Cronin Jr et al., 2000). Companies now view post-sale support as a key competitive advantage, as quick responses to customers' needs help maintain product performance and build trust.

However, traditional methods for managing spare parts face significant challenges. Manufacturers often struggle to produce and store many types of spare parts, especially those with low or unpredictable demand. Keeping large inventories of rarely used parts is expensive, and many companies eventually stop making these parts due to low profits. This forces customers to either stockpile parts themselves or wait for costly replacements from third-party suppliers. In short, conventional spare parts systems suffer from long delivery times, high storage costs, and outdated parts, especially for older products.

Additive manufacturing (AM), commonly known as 3D printing, offers a new solution. AM builds objects layer by layer using digital designs. Initially used for prototypes, AM is now widely applied in industries like aerospace, automotive, and healthcare. For post-sale service, AM allows companies to store digital designs of spare parts instead of physical inventories. When a part is needed, it can be printed on-demand at central facilities or even at repair sites. This approach reduces waiting times for repairs and eliminates the need for large inventories. Early industry surveys have indicated a broad expectation that AM will play a major role in spare parts supply soon (Geissbauer et al., 2017).

This paper explores how additive manufacturing can transform post-sale services through on

demand spare parts production. The discussion begins with a review of relevant literature and industry reports detailing the challenges of conventional spare parts management as well as the proposed benefits of additive manufacturing in this context. The methodology for examining two qualitative case studies is then described. The first case study looks at GE Aviation (a leading aerospace manufacturer and service provider), and the second examines an example from the railway industry (Deutsche Bahn, a major train operator), both of which have integrated AM into their post-sale support operations.

Subsequently, the effects of additive manufacturing on repair timelines, inventory management, and costs are discussed. Broader challenges in adopting this technology, such as limitations in technology and the need for design standardization, are also addressed. Finally, a balanced view of the current and future roles of additive manufacturing in post-sale services is presented, along with practical suggestions for companies considering this technology.

2. Challenges in Traditional Spare Parts Production

Providing fast and affordable spare parts support using traditional manufacturing methods is known to be difficult. Figure 1 shows a diagram drawn from the spare parts statistics of the British Royal Air Force (Haan, 2021). The diagram shows that only a few parts in high demanding while most are rarely used. This “long tail” pattern is commonly observed in spare parts demand across various industries, meaning companies must manage many different parts, each with low and irregular demand (Turrini & Meissner, 2019).

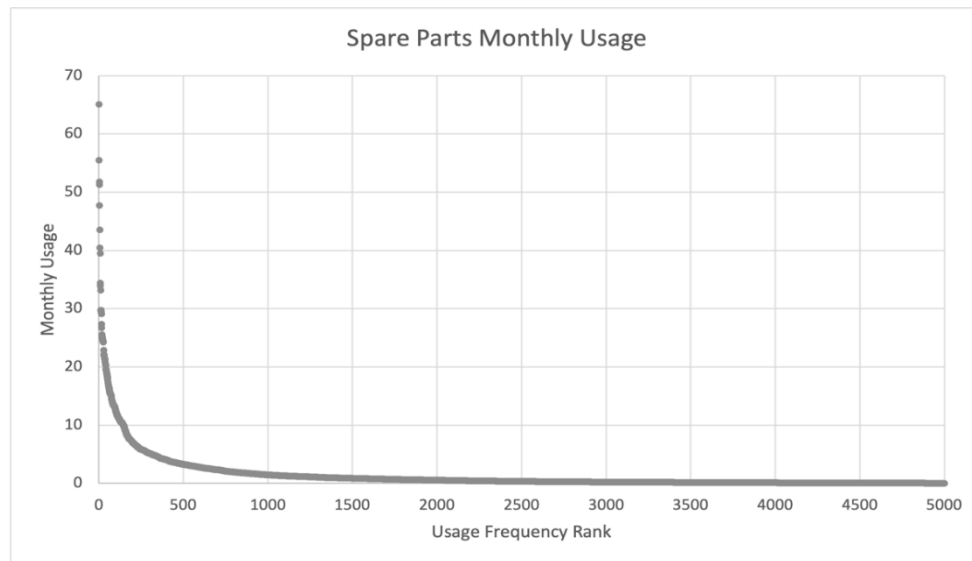


Figure 1. Spare Parts Usage Frequency in RAF

To avoid equipment downtime, companies typically store large numbers of spare parts in warehouses for years sometimes decades. A study by Geissbauer et al. (2017) found that around 40% of companies have over 5% of their spare parts inventory classified as obsolete. This results in high storage costs and money stuck in unused inventory. Moreover, for older equipment, replacement parts may no longer be produced, forcing companies to either place costly small orders or rebuild production tools just to make a few parts. In the railway industry, for example, a large operator had to “stockpile an ever-increasing amount of spare parts in multiple warehouses... to keep its aging train fleet operational” (Geissbauer et al., 2017), and once those stocks were depleted, the only option was custom-fabricating replacements in small lots at great expense. Such rigid supply

chains and slow production processes often lead to long repair delays. If a part is not in stock, waiting times can stretch to weeks or months, leaving equipment unusable.

A study by Cohen et al. (2006) has shown that 50% of consumers with problems faced unnecessary delays in getting vehicles repaired because of spare parts supply issues. This delay directly connects to lower customer satisfaction (Feinberg et al., 1996).

Another problem is predicting spare parts demand over a product's lifetime. Due to uncertainty and the large variety of parts, companies often stock too many parts to avoid shortages. This leads to financial losses if parts become outdated (Baluch et al., 2013). On the other hand, stocking too few parts risks shortages and expensive downtime. Even with better inventory management tools, studies show that spare parts forecasting remains a major challenge (Mor et al., 2021; Wagner & Lindemann, 2008). In short, traditional spare parts systems struggle to balance overstocking (wasting money) and understocking (risking downtime), and conventional manufacturing cannot efficiently produce small batches of parts quickly.

Making customized products is also a big problem in traditional manufacturing, especially in the medical field. For example, traditional hearing aids require labor-intensive crafting of shells to fit each wearer's ear canal. This manual process was time-consuming and often yielded imperfect fits, causing discomfort or multiple adjustments (Tan et al., 2022). Customers also faced painfully long waits for their custom devices (Sandström, 2016).

3. Additive Manufacturing in Post-Sale

Additive manufacturing is reshaping post-sale services by offering faster, more flexible, and cost-efficient solutions. This section explores how AM enhances operations through cost reduction, customization, quicker delivery, and sustainability. Real-world examples and research show its growing impact across industries.

3.1. Cost Reduction

AM lowers post-sale service costs by using a digital library of spare part designs. Instead of storing physical parts in warehouses, companies keep digital files and print parts only when needed (Sirichakwal & Conner, 2016). This "print-on-demand" approach removes the need for large inventories, reducing costs for storage, outdated parts, and unused capital (Attaran, 2017a; Holmström et al., 2010). This method is especially helpful for parts with low demand or those needed for older/discontinued products, where physical stockpiles often become obsolete (Holmström & Gutowski, 2017; Khajavi et al., 2014). The expenses saved can be used to further improve post-sale service quality thus led to greater customer satisfaction (Izogo & Ogba, 2015).

Empirical research supports these benefits. Heinen and Hoberg (2019) reported that about 8% of a manufacturer's aftermarket spare parts could be economically 3D-printed, significantly cutting the need for physical stock. Additionally, the U.S. Navy has successfully 3D-printed spare cooling ducts for F-18 fighter jets, showcasing the practicality of on-demand part production in the field (Khajavi et al., 2014). More broadly, case analyses show that AM-produced spares can be cheaper than conventionally made parts when considering reduced material waste and avoided batch production or inventory costs (Lastra et al., 2022). Maintenance organizations have reported substantial cost reductions by integrating on-demand AM for spare parts, demonstrating successful real-world implementation of digital inventory models (Kostidi et al., 2021; Westerweel et al., 2021).

3.2. Personalized Repairs and Customization

One significant advantage of AM is its ability to deliver personalized repairs. Traditional

manufacturing processes favor mass production, making one-off or tailored parts both difficult and expensive. In contrast, AM excels at producing complex or unique geometries directly from digital files, thereby enabling “lot size one” production without incurring prohibitive costs. This flexibility is particularly beneficial in the medical device industry. Especially, nearly all of custom in-ear hearing aids and dental copings are now produced via additive manufacturing. Unlike the traditional labor-intensive crafting, the design of AM made hearing aids can be easily modified to ensure each device is perfectly tailored to the wearer, greatly improve custom satisfaction (Banker, 2013; Sandström, 2016; Tan et al., 2022).

3.3. Faster Spare Parts Production and Delivery

One of the most immediate benefits of AM is the dramatic reduction in lead times. Traditional supply chains often require weeks or months for spare parts delivery, while AM can produce critical components within days or even hours. Distributed manufacturing models allow local production at repair centers, which cuts down on shipping times and minimizes downtime (Ahlsell et al., 2022). For instance, Deutsche Bahn has reported that implementing 3D printing in its maintenance operations has resulted in substantially faster turnaround times for spare parts (Brickwede, 2017; Geissbauer et al., 2017). As previous studies have shown, reducing delays in spare parts delivery will lead to faster repair (Cohen et al., 2006) and higher customer satisfaction (Feinberg et al., 1996).

3.4. Sustainability Benefits

AM supports a shift toward sustainability by enabling the refurbishment of components rather than full replacement. This approach minimizes waste and reduces the overall environmental footprint (Attaran, 2017b; Ma et al., 2018). GE Aviation, for example, has integrated AM into its repair operations, resulting in fewer parts being scrapped and reduced energy consumption (GEAerospace, 2018).

4. Case Studies

To better understand how AM is being used in real-world applications, this section explores two leading examples from the aerospace and railway sectors. GE Aviation and Deutsche Bahn offer valuable insights into how AM can transform post-sale support by addressing issues like spare part availability, lead time reduction, and cost efficiency. Their experiences demonstrate not only the potential benefits of AM but also the strategic approaches needed to implement effectively across different industries.

4.1. GE Aviation

GE Aviation, a division of General Electric, is a major manufacturer of jet engines for commercial and military aircraft, and it also operates a global service network for engine maintenance and repair. GE has been investing in additive manufacturing for well over a decade, initially using it to produce new engine components. For example, the redesigned LEAP engine fuel nozzle is printed as a single part (GEAerospace, 2018).

Building on that expertise, GE Aviation has increasingly applied AM to its post-sale support activities, with the goals of speeding up engine repairs and minimizing aircraft downtime. By using metal 3D printing in its maintenance shops, GE can restore parts much faster than with traditional methods. At GE’s Singapore engine overhaul facility, technicians using AM can repair twice as many parts per day as before, with customers “seeing their parts return... more quickly” (Listek, 2022). In practice, on-demand local printing of replacement components means airlines no longer wait weeks or months for spares to arrive. Industry analysts note that printing parts closer to the point of use

speeds up repairs, as replacements can be supplied rapidly on-site – reducing downtime and even allowing airlines to cut back on large spare inventory warehouses (Stretton, 2024). These faster turnaround times directly translate into higher fleet availability and improved customer satisfaction.

AM also helps GE support aging aircraft fleets by producing hard-to-find spare parts on demand. Many older engines have diminishing supplier bases, and low-volume orders for legacy components are often unattractive to conventional manufacturers. GE's partnership with the U.S. Air Force showcased how AM can fill this gap: a cobalt-chrome sump cover for the F110 engine was 3D printed to replace a part that traditionally took 2–3 years to procure (Davies, 2020). Additive manufacturing provided an alternate source for this legacy part, ensuring the continued operation of aircraft entering their sixth decade of service. In general, AM's flexibility to produce one-off or low-volume parts without special tooling makes it ideal for legacy support, offering a cost-effective way to sustain older aircraft when original parts are no longer in production (Mohd Yusuf et al., 2019). GE executives even envision a future "printing spare parts on-demand without... inventory," though they acknowledge certification, and scaling will take time (Listek, 2022).

Integrating AM into maintenance, repair, and overhaul (MRO) yields significant cost benefits for GE and its customers. On-demand production means fewer spares need to be stockpiled, freeing up capital and reducing the risk of obsolescent inventory (Uriondo et al., 2015; Wagner & Walton, 2016). Because 3D printing doesn't require casting molds or dedicated tooling, it can be more cost-efficient for low-volume parts. GE has found that switching certain engine parts from castings to AM can cut unit cost by up to 35%, even after retiring old tooling, thanks to streamlined production and material savings (Staff, 2021). In GE's own repair operations, metal AM has improved productivity per technician and shrunk required floor space by one-third, indicating lower overhead. These efficiencies, combined with shorter lead times, help airlines save on operational costs (by avoiding prolonged outages) while GE reduces its service costs – a win-win that ultimately improves customer satisfaction through more affordable and reliable support.

GE Aviation's use of AM in aftermarket services has yielded tangible successes highlighted in industry reports. Its Engine Services Singapore facility became the world's first MRO shop approved for powder-bed metal printing in commercial engine repairs (Everett, 2022). Since then, GE has rapidly scaled up additive repairs for engine blades and other components, doubling repair throughput and cutting turnaround times (Listek, 2022). The U.S. Air Force collaboration is another case study demonstrating improved fleet supportability – officials noted that AM has "incredible potential to improve... supportability" and readiness for legacy engines (Davies, 2020). Academic reviews of aerospace AM corroborate these outcomes, reporting that deploying AM in spare parts supply chains can reduce maintenance downtime and costs while enabling decentralized production (Mohd Yusuf et al., 2019). By embracing additive manufacturing for both new production and MRO, GE Aviation has improved its post-sale customer support delivering critical parts faster, lowering costs, and keeping aircraft flying with less disruption (Listek, 2022; Stretton, 2024).

4.2. Deutsche Bahn

Deutsche Bahn (DB), Germany's largest railway operator, faces unique post-sale challenges due to the long service life of its train fleet. With trains operating for decades, ensuring reliable availability of spare parts is critical for safety and avoiding delays. Traditionally, DB maintained extensive physical inventories to avoid running out of parts or long replacement lead times. However, this approach was expensive, wasted storage space, and often left DB with unused parts that were rarely needed.

To address these issues, DB turned to additive manufacturing (AM) as a transformative solution.

Instead of keeping physical parts in stock, DB now stores digital designs of parts and prints them only when needed. This “digital inventory” is especially useful for rare or outdated parts that original manufacturers no longer produce. By using AM, DB avoids the high costs of storing physical parts and reduces the risk of parts becoming obsolete. More importantly, parts that once took months to order can now be printed quickly near where they are needed (Eirich & Brickwede, 2022; Robinson, 2023). Results from a different resource show that the production time is reduced by 75% (EOS, 2019).

One key advantage of AM is the dramatic reduction in lead times. For example, a wheelset bearing cover for a Class 294 locomotive, which was put into service in the 1960s and 1970s, previously took several months to deliver when produced through traditional methods can now be 3D-printed in just 7 hours (Manufacturing, 2019). This faster process greatly reduces train downtime, allowing repairs to finish sooner and keeping more trains available for service. Faster repairs also mean fewer delays for passengers, improving customer satisfaction. Cost efficiency is another major benefit. Traditional methods forced DB to spend heavily on storing many types of spare parts. With AM, parts are made “just in time” instead of “just in case,” freeing up warehouse space and saving money.

The decision to adopt AM was driven by several factors. First, many train parts become outdated over time, and suppliers often stop making them. AM allows DB to produce even small quantities of these parts, ensuring support for older trains. Second, some parts are complex or require customization, making traditional mass production too expensive. AM can create these parts cheaply without needing special molds or tools. Result shows that for some parts, the production costs are reduced by 80% in adopting AM instead of the traditional injection-molding (EOS, 2019). Figure 2 shows a handrail printed with Braille for visually impaired people, improving their satisfaction.



Figure 2. Handrail Printed with Braille for Visually Impaired People

Additionally, AM makes DB’s supply chain more reliable. By printing parts locally instead of relying on distant suppliers, DB avoids delays caused by global supply chain problems. This was especially helpful during crises like the COVID-19 pandemic (Stötzel, 2023).

By adopting 3D printing, Deutsche Bahn has improved its ability to maintain trains, reduced costs, and increased customer satisfaction. Faster repairs, lower inventory expenses, and a more flexible supply chain have helped DB keep trains running smoothly with fewer disruptions (Bahn, 2022).

5. Discussion

The case studies of GE Aviation and Deutsche Bahn, along with findings from various industries and academic sources, show how additive manufacturing (AM) is changing post-sale services. Both examples support the main benefits of AM—reducing lead times and lowering inventory, while also highlighting some practical challenges.

A common benefit is the reduction of repair and replacement times. In both aerospace and rail industries, downtime is very costly because an idle aircraft or train means lost revenue and customer issues. By producing parts on demand, these companies have shortened the time needed to supply the required part. GE's use of AM for repair allowed an engine component to be restored and re-installed much faster than waiting for a new part to arrive. Similarly, DB printing parts locally means a train can be repaired in a matter of days instead of the weeks or even months that might be required to source a part from a distant supplier or to restart a production line. Faster turnarounds directly translate to improved asset availability.

Another important advantage is lowering inventory costs. Deutsche Bahn aimed to reduce its ever-growing inventory by moving from a “just-in-case” stocking model to a “just-in-time” production model through digital inventory and on-demand printing. This change cuts down on the need for large warehouses and reduces related costs such as capital, insurance, handling, and depreciation. GE, although an OEM with an existing supply chain, also benefits by not having to produce and store as many spare parts in advance. For example, if GE can manufacture an old engine part when it is ordered, it does not need to keep that part in storage for many years. Both cases show that AM enables companies to maintain service levels with lower inventory, even though it requires investing in AM technology and digital systems that makes sense for expensive, rarely used parts.

AM also creates new opportunities to support products well beyond their normal service life or when traditional supply chains fail. In the past, once an OEM stopped supporting a product, customers struggled to find spare parts. Now, as seen with GE and Deutsche Bahn, parts can “live forever” as digital blueprints, ready to be made when needed. This approach extends the useful life of complex equipment and improves customer satisfaction, as support continues even for outdated models. GE's ability to produce discontinued parts for old engines and DB's capacity to keep vintage trains running are good examples of this extended support. Moreover, this method could open a new revenue stream, as OEMs might sell digital licenses or printing services for parts instead of physical inventory, thereby changing the post-sale business model.

6. AM Adoption Challenges

While AM offers clear advantages in flexibility, lead time reduction, and inventory management, its adoption in large organizations is not without hurdles. The following sections highlight key challenges encountered during the implementation of AM in real-world industrial settings. These insights, drawn from the experiences of GE Aviation and Deutsche Bahn, underscore the importance of a strategic, multi-disciplinary approach to successfully integrate AM into existing operations.

6.1. Quality & Certification

However, there are challenges to overcome. One major issue is ensuring the quality and reliability of printed parts. In safety-critical industries, there is understandable caution. GE had to thoroughly test the repaired engine component and work with regulators to certify it. This shows that although printing a part can be fast, the necessary tests and certification may take extra time, especially during early adoption. GE managed this by initially focusing on less critical parts, such as nonrotating

components that could first be tested on the ground. In aerospace, as confidence grows (for example, the FAA has approved many AM parts), the process will speed up. For Deutsche Bahn, even though rail standards may be less strict than aerospace, they still had to ensure that a 3D-printed metal part met strength and fatigue requirements. Both companies conducted parallel tests to validate performance, indicating that industry-wide standards and certification processes for AM parts are needed and are still developing.

6.2. Learning Curve

Another challenge is dealing with technical limitations and the learning curve. Both GE and Deutsche Bahn began by using AM only for a select group of parts that clearly benefited from the technology. Identifying these parts required detailed analysis; DB used specialized software to assess its inventory for AM suitability, while GE relied on the expertise of its engineering teams. This shows that adopting AM is not just about buying a printer—it requires careful selection of use cases. Moreover, GE's experience revealed that integrating AM into repairs needed years of research and development (with work at their Bari repair center starting in 2010 and maturing by 2017 (GEAerospace, 2017)). This long R&D process can be a barrier for companies with fewer resources. In contrast, Deutsche Bahn benefited from partnering with external AM service providers and technology companies, suggesting that collaboration with experts may be a good model for other firms.

6.3. Process Integration

Operationally, introducing AM means rethinking logistics and support processes. Deutsche Bahn had to integrate the AM ordering system into its maintenance routines so that technicians could easily start a print order during repairs. GE had to add new inspection routines for parts repaired with AM. Both companies also needed to train their maintenance and supply chain staff to understand AM's possibilities and limits. Sometimes, there may be resistance—for example, technicians might initially trust a printed part less than a traditionally machined one until they see it perform well. Managing this change is an important part of implementing AM.

6.4. Selective Use

It is also important to note that AM is not cost-effective for every spare part. Many parts remain cheaper to mass-produce and stock using conventional methods, especially when demand is steady or high. The ideal use for AM is for low-volume, complex, or rarely used parts, which is clearly the focus in these cases. Companies are not expected to print every spare part; instead, they will combine traditional stocking with printed solutions where it makes both economic and strategic sense. As AM technology improves with faster printing speeds, lower machine and material costs, and larger build volumes, the number of parts that can be produced with AM will likely increase. In the next decades, 3D printing may even capture a significant share of spare parts manufacturing, but until then, a hybrid approach is most likely, and companies must continuously evaluate whether AM or conventional methods work best for each part.

6.5. Infrastructure

Lastly, there are some technical obstacles to consider. Although the cases did not mention problems like machine reliability or material supply in detail, these issues could arise. An AM-based spare parts strategy creates a dependency on printers and raw materials, so companies must have backups, such as multiple printers or alternative suppliers—to avoid a single point of failure. Digital security is also crucial; digital part files must be safeguarded against tampering or intellectual property theft, particularly when transferred between locations. While GE and Deutsche Bahn have

not reported major problems in this area, any large-scale digital inventory system will need strong cybersecurity and intellectual property management.

Overall, AM is transforming post-sale services, but this change is gradual and requires a strategic approach. Companies like GE Aviation and Deutsche Bahn are leading the way by significantly reducing lead times, enabling flexible production, and rethinking inventory management. Their experiences offer valuable lessons for others making the transition. Success depends not only on purchasing AM equipment but also on an integrated approach involving engineering, supply chain, IT, and management support. The benefits can be significant in terms of customer service and cost savings. The balanced view from our research is that AM will increasingly become a powerful addition to the post-sale toolkit, working alongside traditional methods where it adds value.

7. Conclusion

Additive manufacturing is expected to greatly change post-sale support by allowing spare parts to be made on demand. This new method addresses many problems found in traditional spare parts supply, such as long lead times, high inventory costs, difficulties in meeting the wide range of spare parts needs and making customized parts. AM introduces a model of local, just-in-time production using digital inventories. This change can reduce the need for physical stock, speed up repairs, and improve flexibility. For example, GE Aviation used AM to repair jet engine parts faster, and Deutsche Bahn reduced warehouse stock by printing railway parts on demand. In both cases, AM helped improve service levels, reducing downtime and increasing part availability, while lowering overall costs by cutting inventory and avoiding expensive small production runs.

However, this research also showed that moving to an AM-based post-sale model brings some challenges. Technical and regulatory issues, such as part certification, process validation, and material limitations, must be handled carefully. Organizations need to adjust their current maintenance processes and supply chains to include AM. Companies must also develop clear strategies to decide which parts to print and which to keep in stock, using the right tools and expertise for these decisions (Chaudhuri et al., 2021). Early adopters like GE and Deutsche Bahn have demonstrated that these challenges can be overcome by investing in research and development, forming partnerships, and taking a phased approach that focuses on high-impact cases first.

In conclusion, additive manufacturing is a promising and practical tool for improving post-sale service and customer satisfaction across various industries. Its ability to produce spare parts on demand can greatly reduce lead times and inventory costs, leading to more agile and cost-effective support operations, and further leading to greater customer satisfaction. Academic studies support these results, and real-world examples show that they work.

Overall, the evolution of post-sale service with AM shows how digital manufacturing innovations can refresh traditional operational models. Evidence so far suggests that companies adopting this change will gain a competitive advantage in customer service and efficiency. In the future, seeing a critical spare part produced by a 3D printer right when needed for a repair may become common, fulfilling the promise of truly responsive, on-demand post-sale support.

8. Disclaimer Statements

Funding: None

Conflict of Interest: None

9. References

- Ahlsell, L., Jalal, D., Khajavi, S. H., Jonsson, P., & Holmström, J. (2022). Additive manufacturing of slow-moving automotive spare parts: A supply chain cost assessment. *Journal of Manufacturing and Materials Processing*, 7(1), 8. <https://doi.org/10.3390/jmmp7010008>
- Attaran, M. (2017a). Additive manufacturing: The most promising technology to alter the supply chain and logistics. *Journal of Service Science and Management*, 10(03), 189. <https://doi.org/10.4236/jssm.2017.103017>
- Attaran, M. (2017b). The rise of 3-d printing: The advantages of additive manufacturing over traditional manufacturing. *Business horizons*, 60(5), 677–688. <https://doi.org/10.1016/j.bushor.2017.05.011>
- Bahn, D. (2022). 3d printing at db. On-line: https://www.deutschebahn.com/en/3d_printing-6935100,
- Baluch, N. H., Abdullah, C. S., & Mohtar, S. (2013). Evaluating effective spare-parts inventory management for equipment reliability in manufacturing industries. *European Journal of Business and Management*, 5(6), 69–76. <https://repo.uum.edu.my/id/eprint/16093>
- Banker, S. (2013). 3d printing revolutionizes the hearing aid business. On-line: <https://www.forbes.com/sites/stevebanker/2013/10/15/3d-printing-revolutionizes-the-hearing-aid-business/>
- Brickwede, S. (2017). Deutsche bahn: Sweet fruits are hard to reach: How to find intriguing 3d printing cases. Connectivity, Spare Parts Planning and 3D Printing workshop held at Aalborg University, Copenhagen.
- Chaudhuri, A., Gerlich, H. A., Jayaram, J., Ghadge, A., Shack, J., Brix, B. H., Hoffbeck, L. H., & Ulriksen, N. (2021). Selecting spare parts suitable for additive manufacturing: A design science approach. *Production Planning & Control*, 32(8), 670–687. <https://doi.org/10.1080/09537287.2020.1751890>
- Cohen, M. A., Agrawal, N., & Agrawal, V. (2006). Winning in the aftermarket. *Harvard business review*, 84(5), 129.
- Cronin Jr, J. J., Brady, M. K., & Hult, G. T. M. (2000). Assessing the effects of quality, value, and customer satisfaction on consumer behavioral intentions in service environments. *Journal of retailing*, 76(2), 193–218. [https://doi.org/10.1016/S0022-4359\(00\)00028-2](https://doi.org/10.1016/S0022-4359(00)00028-2)
- Davies, S. (2020). Ge working with united states air force to 3d print spare aircraft parts. On-line: <https://www.tctmagazine.com/additive-manufacturing-3d-printing-news/ge-workingwith-united-states-air-force-to-3d-print-spare-ai/>
- Haan, D.B. de. (2021). Benchmarking spare parts demand forecasting methods. *Business Economics*. On-line: <http://hdl.handle.net/2105/60771>
- Eirich, A., & Brickwede, S. (2022). Article: 3d printing as a digital manufacturing technology. On-line: <https://www.db-fzi.com/fahrzeuginstandhaltung-en/Individual-Solutions/3D-druck-7314184>
- EOS. (2019). The fast track to 3d printed custom train parts with additive manufacturing by eos. On-line: <https://www.eos.info/industries/customer-success-stories/deutschebahn-3d-printed-spare-parts-for-trains>
- Everett, H. (2022). Ge aviation first to gain approval for metal am for 3d engine component repair. On-line: <https://3dprintingindustry.com/news/ge-aviation-first-to-gain-approval-formetal-am-for-3d-engine-component-repair-207123/>
- Feinberg, R. A., Widdows, R., & Steidle, R. (1996). Customer (dis) satisfaction and delays: The robust negative effects of service delays. *Journal of consumer satisfaction, dissatisfaction and complaining behavior*, 9, 81–85.
- GEAerospace. (2017). Scan and fix: Ge aviation uses additive technology to fast track engine component repairs. On-line: <https://www.geaerospace.com/news/articles/manufacturing/scanand-fix-ge-aviation-uses-additive-technology-fast-track-engine>
- GEAerospace. (2018). Manufacturing milestone: 30,000 additive fuel nozzles. On-line: <https://www.geaerospace.com/news/articles/manufacturing/manufacturing-milestone-30000-additivefuel-nozzles>
- Geissbauer, R., Wunderlin, J., & Lehr, J. (2017). The future of spare parts is 3d: A look at the challenges and opportunities of 3d printing. On-line: <https://www.strategyand.pwc.com/gx/en/insights/2017/the-future-spare-parts-3d/the-future-of-spare-parts-is-3d.pdf>

- Heinen, J. J., & Hoberg, K. (2019). Assessing the potential of additive manufacturing for the provision of spare parts. *Journal of Operations Management*, 65(8), 810–826. <https://doi.org/10.1002/joom.1054>
- Holmström, J., & Gutowski, T. (2017). Additive manufacturing in operations and supply chain management. *J. Ind. Ecol*, 21, 21–24. <https://doi.org/10.1111/jiec.12580>
- Holmström, J., Partanen, J., Tuomi, J., & Walter, M. (2010). Rapid manufacturing in the spare parts supply chain: Alternative approaches to capacity deployment. *Journal of manufacturing technology management*, 21(6), 687–697. <https://doi.org/10.1108/17410381011063996>
- Izogo, E. E., & Ogba, I.-E. (2015). Service quality, customer satisfaction and loyalty in automobile repair services sector. *International Journal of Quality & Reliability Management*, 32(3), 250–269. <https://doi.org/10.1108/IJQRM-05-2013-0075>
- Khajavi, S. H., Partanen, J., & Holmström, J. (2014). Additive manufacturing in the spare parts supply chain. *Computers in industry*, 65(1), 50–63. <https://doi.org/10.1108/RPJ-03-2017-0052>
- Kostidi, E., Nikitakos, N., & Progoulakis, I. (2021). Additive manufacturing and maritime spare parts: Benefits and obstacles for the end-users. *Journal of Marine Science and Engineering*, 9(8), 895. <https://doi.org/10.3390/jmse9080895>
- Lastra, R., Pereira, A., Díaz-Cacho, M., Acevedo, J., & Collazo, A. (2022). Spare parts made by additive manufacturing to improve preventive maintenance. *Applied Sciences*, 12(20), 10564. <https://doi.org/10.3390/app122010564>
- Listek, V. (2022). Ge aviation singapore is first mro facility to repair jet engines with metal 3d printing. On-line: <https://3dprint.com/289541/ge-aviation-singapore-is-first-mro-facility-to-repair-jet-engines-with-metal-3d-printing/>
- Ma, J., Harstvedt, J. D., Dunaway, D., Bian, L., & Jaradat, R. (2018). An exploratory investigation of additively manufactured product life cycle sustainability assessment. *Journal of Cleaner Production*, 192, 55–70. <https://doi.org/10.1016/j.jclepro.2018.04.249>
- Manufacturing, A. (2019). Application spotlight: 3d printing in the rail industry. On-line: <https://amfg.ai/2019/10/15/application-spotlight-3d-printing-in-the-rail-industry>
- Mohd Yusuf, S., Cutler, S., & Gao, N. (2019). The impact of metal additive manufacturing on the aerospace industry. *Metals*, 9(12), 1286. <https://doi.org/10.3390/met9121286>
- Mor, R., Bhardwaj, A., Kharka, V., & Kharub, M. (2021). Spare parts inventory management in warehouse: A lean approach. *International Journal of Industrial Engineering & Production Research*, 32(2), 4. <https://doi.org/10.22068/ijiepr.32.2.179>
- Robinson, E. (2023). Db use 3d printing to transform train maintenance. On-line: <https://www.globalrailwayreview.com/news/144352/db-use-3d-printing-to-transform-train-maintenance/>
- Sandström, C. G. (2016). The non-disruptive emergence of an ecosystem for 3D Printing—Insights from the hearing aid industry's transition 1989–2008. *Technological Forecasting and Social Change*, 102, 160–168. <https://doi.org/10.1016/j.techfore.2015.09.006>
- Sirichakwal, I., & Conner, B. (2016). Implications of additive manufacturing for spare parts inventory. *3D printing and Additive Manufacturing*, 3(1), 56–63. <https://doi.org/10.1089/3dp.2015.0035>
- Staff, G. A. N. (2021). Game changer: Four parts proving additive manufacturing can compete with casting on cost. On-line: <https://www.geaerospace.com/news/articles/technology/gamechanger-four-parts-proving-additive-manufacturing-can-compete-casting-cost>
- Stötzel, S. (2023). Artikel: 3d-druck bringt züge schneller aufs gleis. On-line: https://www.deutschebahn.com/de/presse/pressestart_zentrales_uebersicht/3D-Druck-bringt-Zuegeschneller-aufs-Gleis-10641506
- Stretton, J. (2024). How additive manufacturing can help to transform the aerospace sector. On-line: <https://www.flightglobal.com/aerospace/how-additive-manufacturing-can-help-to-transform-the-aerospace-sector/157092.article>
- Tan, C. K. L., Goh, Z. H., De Chua, K. W., Kamath, S., Chung, C. K. R., Teo, W. B. Y., Martinez, J. C., Dritsas, S., & Simpson, R. E. (2022). An improved hearing aid fitting journey; the role of 3d scanning, additive manufacturing, and sustainable practices. *Materials Today: Proceedings*, 70, 504–511. <https://doi.org/10.1016/j.matpr.2022.09.536>
- Turrini, L., & Meissner, J. (2019). Spare parts inventory management: New evidence from distribution fitting.

- European Journal of Operational Research, 273(1), 118–130.
<https://doi.org/10.1016/j.ejor.2017.09.039>
- Uriondo, A., Esperon-Miguez, M., & Perinpanayagam, S. (2015). The present and future of additive manufacturing in the aerospace sector: A review of important aspects. *Proceedings of the Institution of Mechanical Engineers, Part G: Journal of Aerospace Engineering*, 229(11), 2132–2147.
<https://doi.org/10.1177/0954410014568797>
- Wagner, S. M., & Lindemann, E. (2008). A case study-based analysis of spare parts management in the engineering industry. *Production planning & control*, 19(4), 397–407.
<https://doi.org/10.1080/09537280802034554>
- Wagner, S. M., & Walton, R. O. (2016). Additive manufacturing's impact and future in the aviation industry. *Production Planning & Control*, 27(13), 1124–1130. <https://doi.org/10.1080/09537287.2016.1199824>
- Westerweel, B., Basten, R., denBoer, J., & vanHoutum, G.-J. (2021). Printing spare parts at remote locations: Fulfilling the promise of additive manufacturing. *Production and Operations Management*, 30(6), 1615–1632. <https://doi.org/10.1111/poms.13298>

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INVESTIGATING MECHANICAL BEHAVIOURS OF FIRE-RETARDANT FIBER COMPOSITES IN AGGRESSIVE AVIATION FLUIDS

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Abstract

This study investigates the effects of aviation fluid exposure on aerospace-grade carbon and glass fiber composites. Five critical fluids—hydraulic fluid, dry cleaning solvent, isopropyl alcohol deicer, methyl ethyl ketone (MEK), and a hydraulic fluid/water mixture—were used to simulate real-world environmental conditions. Composite specimens were exposed for durations of 15 days and 30 days. Mechanical properties were assessed through short beam shear tests to determine the interlaminar shear strength (ILSS) of the aged specimen, while fluid uptake was measured gravimetrically. Results indicate that MEK consistently caused the most significant degradation in mechanical properties and the highest fluid absorption for both composite types. Glass fiber composites exhibited greater susceptibility to environmental effects compared to carbon fiber composites. The time-dependent nature of fluid absorption correlated strongly with changes in mechanical properties. These findings highlight the critical importance of specific fluid-composite compatibility testing in aerospace material selection and design. The study underscores the need for enhanced protective strategies and long-term durability assessments to improve the reliability and performance of composite structures in aerospace applications. Future research directions are suggested to address these challenges.

Keywords: *Fiber-Reinforced Composites; Aeronautic Fluids; Short Beam Shear; Interlaminar Shear Strength; Moisture Ingression; Fracture Mechanism.*

1. Introduction

The aerospace industry has long been at the forefront of materials innovation, constantly seeking advanced composites that offer superior mechanical properties while meeting stringent safety requirements. Among these requirements, fire resistance and chemical stability in the presence of aviation fluids are paramount. Fire-retardant fiber composites have emerged as promising materials for aerospace applications, offering a combination of lightweight properties, high strength-to-weight ratios, and enhanced fire resistance compared to traditional materials (Soutis, 2020; Weitsman &

Elahi, 2000). However, the long-term performance of these composites when exposed to aggressive aviation fluids remains a critical area of investigation. Aviation fluids, including hydraulic fluids, jet fuels, and de-icing agents, create a challenging environment for materials used in aircraft structures and components. These fluids can potentially degrade the mechanical properties of composites over time, compromising their structural integrity and safety (Mouritz et al., 2009). Understanding the behavior of fire-retardant fiber composites in such environments is crucial for ensuring the longevity and reliability of aerospace structures. The development of fire-retardant composites has been a significant focus of research in recent years, involving the incorporation of flame-retardant additives into the matrix, the use of inherently flame-resistant fibers, and the application of fire-resistant coatings (Hamzat et al., 2023; Rhee et al., 2004). For instance, Kandola et al. (Kandola et al., 2015) investigated the fire performance of glass fiber-reinforced epoxy composites with different types of fire retardants, demonstrating improved flame resistance without significant compromise to mechanical properties.

While the fire-retardant properties of these composites have been extensively studied, their behavior in aggressive chemical environments typical of aviation applications has received comparatively less attention. Previous work by Zhang et al. (Zhang et al., 2018) examined the effects of jet fuel exposure on the tensile properties of carbon fiber-reinforced epoxy composites, revealing a gradual degradation in strength over time. Similarly, Ali et al. (Ali Charfi et al., 2020) investigated the impact of hydraulic fluid on the interlaminar shear strength of glass fiber-reinforced composites, highlighting the need for careful material selection in fluid-exposed applications. The interaction between fire-retardant additives and aviation fluids presents a complex challenge. While these additives enhance the flame resistance of composites, they may also affect the material's chemical resistance and long-term durability when exposed to aggressive fluids. Mouritz et al. (Mouritz et al., 2009) noted that some fire-retardant additives could potentially increase the susceptibility of composites to fluid absorption, leading to accelerated degradation of mechanical properties. Recent advancements in nano-engineered composites offer promising avenues for enhancing both fire resistance and chemical stability. For example, Wang et al. (Wang et al., 2024) demonstrated improved flame retardancy and mechanical properties in epoxy composites reinforced with graphene oxide and carbon nanotubes. However, the performance of these advanced composites in aggressive fluid environments remains to be fully explored. In light of these considerations, there is a clear need for comprehensive research investigating the mechanical behaviors of fire-retardant fiber composites when exposed to aggressive aviation fluids.

This study aims to address this gap by examining the effects of prolonged exposure to common aviation fluids on the mechanical properties of various fire-retardant composite systems. Through a detailed experimental analysis, we seek to provide insights into the degradation mechanisms of Carbon and Glass fiber composites in Hydraulic fluid (HF), Isopropyl Alcohol Deicing (Iso P), Methyl Ethyl Ketone (MEK), Dry Cleaning Solvents (DES) and HF/water Mixture and understand how aircraft fluid ingress affected the interlaminar shear strength of the laminated composites. These fluids were chosen because they are common fluids that aircraft composites regularly encounter during service. They cover typical operational and maintenance situations, such as hydraulic leaks, cleaning and degreasing, cold-weather deicing, paint or adhesive removal, and fluid contamination in wet environments. Their selection therefore mirrors real-world conditions that can greatly affect the long-term durability of aerospace composites.

2. Experimentation

2.1 Materials and Composite Fabrication

In the current investigation, two aerospace-grade prepreg composites were utilized: Unidirectional Carbon Fabric and 7781 E-Glass, sourced from Fibre Glast Development Corp., Ohio. The prepreg panels, comprising carbon and glass fibers with a fiber-to-resin volume ratio of 55.57:44.43, were fabricated with a symmetric cross-ply [0/90] configuration and cured in accordance with the manufacturer's specifications. The fabrication process involved arranging four 12 x 8-inch squares of material in eight layers atop an aluminum plate, adhering to the prescribed layup pattern. A solid release film, extending approximately 1 inch beyond the material edges, was applied to fully encapsulate the layered material. A breather ply was then positioned over the release film to ensure uniform vacuum distribution. Subsequently, the entire laminate assembly was enveloped in a vacuum bag, with additional bagging material incorporated to prevent corner bridging. An aluminum plate was placed on top, and a full vacuum was applied. The material was processed in a mold heated to 120 °C under an applied pressure of 25 inHg. These conditions were maintained for a 90-minute consolidation period, followed by cooling to ambient temperature while holding the pressure constant before demolding. Test specimens were extracted from the cured laminates using a water-cooled, diamond-impregnated saw. The edges were refined using fine-grit abrasive paper to ensure dimensional accuracy and surface quality. Final specimen dimensions were machined to conform to the requirements of the respective test standards. This methodology ensures the production of high-quality, aerospace-grade composite specimens suitable for rigorous mechanical testing and analysis. Fig. 1 shows the stages involved in the fabrication of the laminated composite used in this study.

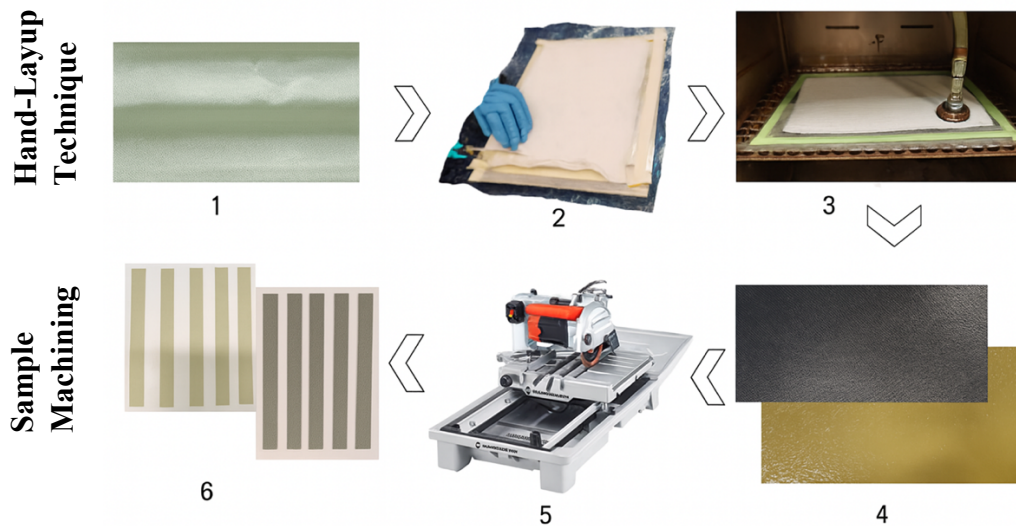


Fig. 1. Stepwise Stages in The Composite Manufacturing Process. (1) Fabric Preparation, (2) Hand Lay-Up of Fiber Layers with Resin Application, (3) Vacuum Bagging and Curing in An Oven, (4) Cured Laminate, (5) Sample Machining, (6) Prepared Composite Test Specimens.

2.2 Details of Immersion and Mechanical Test

To elucidate the fundamental mechanisms governing the interaction between aviation fluids and

composite materials, an extensive investigation was conducted on the behavior of composite specimens exposed to various aircraft-related fluids. Five critical aviation fluids were selected for this study: Hydraulic fluid (Skydrol), dry cleaning solvent type II, isopropyl alcohol deicer, methyl ethyl ketone, and a hydraulic fluid/water mixture. These fluids were chosen due to their prevalence in aerospace applications and the practical challenges associated with protecting composites from their exposure in operational environments. Fig. 2 provides a comprehensive overview of the experimental setup for exposing composite specimens to the selected aircraft fluids. The exposure protocol was designed to simulate both short-term and long-term effects. The composite coupons were subjected to exposure periods of 15 and 30 days to enabling the assessment of prolonged fluid interaction effects.

To quantify the impact of these aggressive environments on the mechanical integrity of the composites, short beam shear (SBS) tests were performed. The SBS test relies on classical (Bernoulli-Euler) beam theory to determine the interlaminar shear stress (ILSS). The maximum ILSS in a rectangular cross-section beam subjected to three-point bending is located at the mid-thickness of the beam, between the center and end supports. This value can be computed as follows:

$$\tau = \frac{3}{4} \cdot \frac{P_B}{w \cdot t} \quad (1)$$

at which P_B represents the maximum load, whereas w and t represent the width and thickness of the beam, respectively. The samples were chosen with a span to thickness ratio of $w/t = 4$, as advised by the ASTM standards (ASTM D 2344) (Adams & Lewis, 1997; Shindo et al., 2001; Sritharan & Askari, 2021). During the process of bending in SBS, the load grows in direct proportion to the deformation until it reaches a maximum load. These tests were conducted on both unexposed control specimens and samples that had undergone fluid exposure. This comparative analysis allowed for a precise evaluation of the changes in mechanical properties induced by the various aviation fluids.

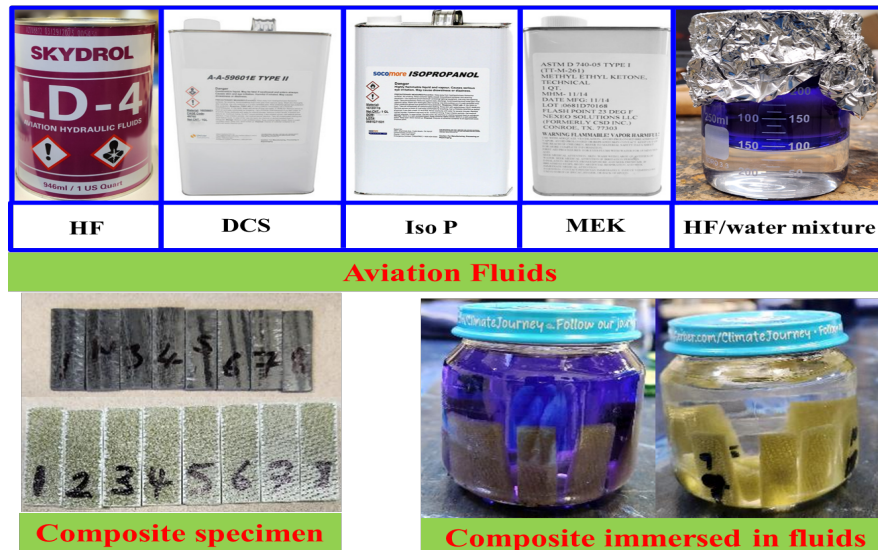


Fig. 1. Overview Of Composite Exposure to Aviation Fluids. The Selected Fluids Include (HF) Hydraulic Fluid, (DCS) Dry Cleaning Solvent, (Iso P) Isopropyl Alcohol, (MEK) Methyl Ethyl Ketone, And A Hydraulic Fluid/Water Mixture. Composite Specimens (Bottom Left) Were Prepared and Subsequently Immersed in These Fluids (Bottom Right) To Simulate Service-Related Environmental Exposure.

3. Results and Discussion

Figure 3 presents the stress-strain relationships for carbon fiber (a) and glass fiber (b) composite specimens exposed to various aviation fluids, compared to pristine (unexposed) samples. The interlaminar stress-strain response of composite specimens after exposure to the selected fluids provides crucial insights into the mechanical behavior of these aerospace-grade composites under different environmental conditions. For the carbon fiber composites (Figure 3a), the pristine specimen exhibits a nonlinear stress-strain curve with the highest ultimate interlaminar stress, reaching approximately 72 MPa. Specimens exposed to hydraulic fluid (HF), isopropyl alcohol (Iso P), dry cleaning solvent (DCS), and the hydraulic fluid/water mixture show similar initial stiffness to the pristine sample, but with slightly lower ultimate stresses ranging from about 65-70 MPa. The methyl ethyl ketone (MEK) exposed specimen demonstrates a significantly different behavior, with markedly reduced stiffness and ultimate stress (approximately 48 MPa), indicating a more severe degradation of the composite's mechanical properties. In contrast, the glass fiber composites (Figure 3b) display more pronounced differences between the exposed and pristine specimens. The pristine sample exhibits the highest initial stiffness and ultimate interlaminar stress (about 50 MPa). All fluid-exposed specimens show reduced stiffness and strength compared to the pristine condition. The MEK-exposed sample again shows the most significant degradation, with the lowest ultimate stress (approximately 30 MPa) and altered stress-strain behavior.

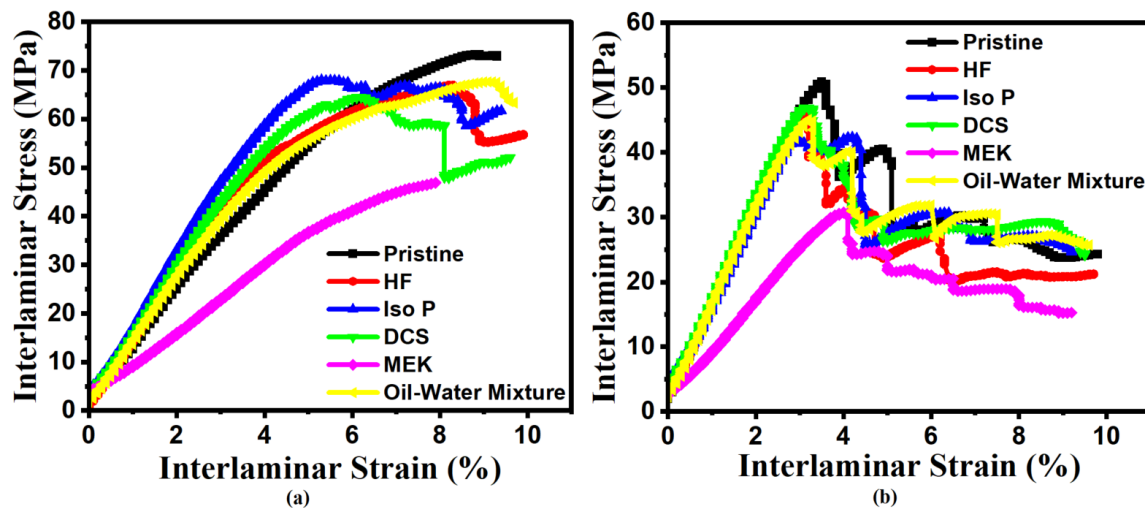


Fig. 2. Interlaminar Stress–Strain Response of Composite Specimens After Exposure to Aviation Fluids. (A) Carbon Fiber Composites And (B) Glass Fiber Composites Compared to Pristine (Unexposed) Specimens. Aviation Fluids Include: HF = Hydraulic Fluid, DCS = Dry Cleaning Solvent, Iso P = Isopropyl Alcohol, MEK = Methyl Ethyl Ketone, And Oil–Water Mixture = Hydraulic Fluid/Water Mixture. Stress Is Reported in Megapascals (Mpa) And Strain in Percentage (%).

Notably, both composite types exhibit multiple stress drops in their stress-strain curves, particularly after reaching their ultimate stress. This phenomenon is more pronounced in the glass fiber composites and likely indicates progressive failure modes such as matrix cracking, delamination, or fiber breakage. The varying degrees of degradation observed across different fluid exposures suggest that each fluid interacts uniquely with the composite materials. The consistent severe impact of MEK on both carbon and glass fiber composites indicates its particularly aggressive nature towards these aerospace materials.

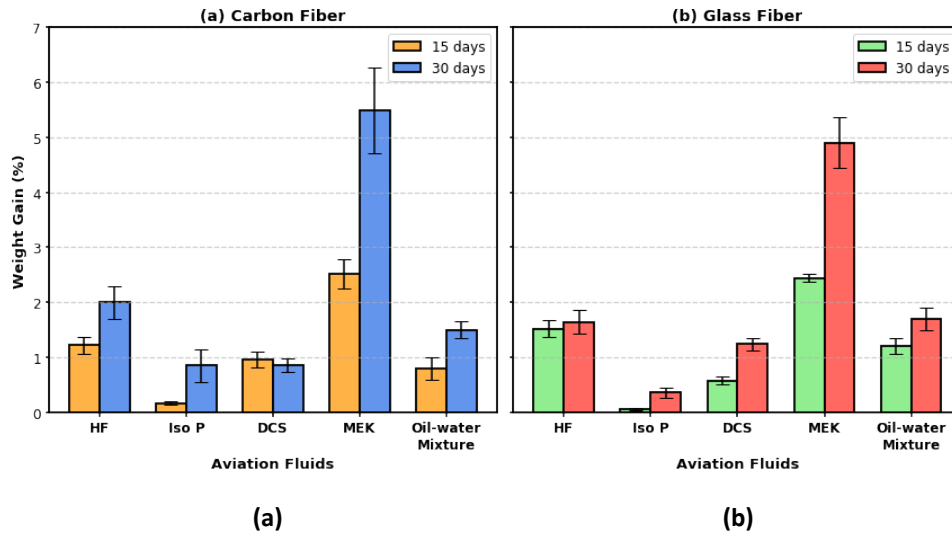


Fig. 3. Aviation Fluids Uptake of The Composite Specimen After Exposure. (A) Carbon Fiber Composites (B) Glass Fiber Composites After 15 And 30 Days of Immersion. Aviation Fluids Include: HF = Hydraulic Fluid, DCS = Dry Cleaning Solvent, Iso P = Isopropyl Alcohol, MEK = Methyl Ethyl Ketone, And Oil-Water Mixture = Hydraulic Fluid/Water Mixture.

Figure 4 illustrates the aviation fluid uptake of carbon fiber (a) and glass fiber (b) composite specimens over 15 and 30-day exposure periods. For carbon fiber composites, hydraulic fluid (HF), Isopropyl alcohol (Iso P), and dry-cleaning solvent (DCS) exhibit minimal fluid absorption, with slight increases from 15 to 30 days. In contrast, methyl ethyl ketone (MEK) demonstrates significantly higher uptake, reaching nearly 4% weight gain after 30 days. The hydraulic fluid/water mixture shows moderate absorption with a notable increase over time. Glass fiber composites generally display higher fluid uptake compared to their carbon fiber counterparts. MEK again exhibits the highest absorption, reaching approximately 3% weight gain after 30 days. Hydraulic fluid and the hydraulic fluid/water mixture show moderate uptake with clear time-dependent increases. Isopropyl alcohol and dry-cleaning solvent, while displaying lower uptake than other fluids for glass fiber, still show higher absorption than in carbon fiber composites.

Most fluids show increased absorption with longer exposure, highlighting the time-dependent nature of this phenomenon; and the variability in uptake across different fluids emphasizes the importance of specific fluid-composite interactions in determining material behavior. These findings provide crucial insights into the fluid absorption characteristics of aerospace composites, directly impacting their mechanical properties and long-term performance in aviation environments. The significant uptake of certain fluids, particularly MEK, underscores the necessity for enhanced protection of composites against prolonged exposure to these substances in aerospace applications.

4. Conclusions

This study provides critical insights into the behavior of aerospace-grade carbon and glass fiber composites when exposed to various aviation fluids. The results demonstrate that fluid exposure can significantly alter the mechanical properties and absorption characteristics of these materials, with the extent of impact varying based on fluid type and exposure duration. Glass fiber composites demonstrated greater susceptibility to environmental effects compared to carbon fiber composites. The time-dependent nature of fluid absorption and its correlation with mechanical property changes

underscore the necessity for comprehensive long-term durability assessments in aerospace material qualification. Future research should focus on developing mitigation techniques and investigating long-term fluid exposure effects under realistic service conditions to improve composite reliability in aerospace environments.

5. Acknowledgments

The authors greatly acknowledge Wichita State University and Turkish Aerospace Industries – USA (TAI – USA) for the technical support of the present study.

6. Disclaimer Statements

Funding: Wichita State University and Turkish Aerospace Industries – USA (TAI – USA)

Conflict of Interest: None

7. References

- Adams, D. F., & Lewis, E. Q. (1997). Experimental assessment of four composite material shear test methods. *Journal of Testing and Evaluation*, 25(2), 174–181. <https://doi.org/10.1520/JTE11475J>
- Ali Charfi, M., Mathieu, R., Chatelain, J.-F., Ouellet-Plamondon, C., & Lebrun, G. (2020). Effect of graphene additive on flexural and interlaminar shear strength properties of carbon fiber-reinforced polymer composite. *Journal of Composites Science*, 4(4), 162. <https://doi.org/10.3390/jcs4040162>
- Hamzat, A. K., Adesina, A. Y., Rasheed, T., & Abdul Samad, M. (2023). Assessing the Tribological Behavior of Nanoclay-Reinforced Epoxy Coatings Under Dry Sliding and Seawater Lubricated Conditions. *Journal of Materials Engineering and Performance*, 32(15), 6905–6914. <https://doi.org/10.1007/s11665-022-07605-7>
- Kandola, B. K., Krishnan, L., Deli, D., & Ebdon, J. R. (2015). Blends of unsaturated polyester and phenolic resins for application as fire-resistant matrices in fibre-reinforced composites. Part 2: Effects of resin structure, compatibility and composition on fire performance. *Polymer Degradation and Stability*, 113, 154–167. <https://doi.org/10.1016/j.polymdegradstab.2014.11.002>
- Mouritz, A. P., Feih, S., Kandare, E., Mathys, Z., Gibson, A. G., Des Jardin, P. E., Case, S. W., & Lattimer, B. Y. (2009). Review of fire structural modelling of polymer composites. *Composites Part A: Applied Science and Manufacturing*, 40(12), 1800–1814. <https://doi.org/10.1016/j.compositesa.2009.09.001>
- Rhee, K. Y., Lee, S. M., & Park, S. J. (2004). Effect of hydrostatic pressure on the mechanical behavior of seawater-absorbed carbon/epoxy composite. *Materials Science and Engineering: A*, 384(1–2), 308–313. <https://doi.org/10.1016/j.msea.2004.06.028>
- Shindo, Y., Wang, R., & Horiguchi, K. (2001). Analytical and experimental studies of short-beam interlaminar shear strength of G-10CR glass-cloth/epoxy laminates at cryogenic temperatures. *J. Eng. Mater. Technol.*, 123(1), 112–118. <https://doi.org/10.1115/1.1286235>
- Soutis, C. (2020). Aerospace engineering requirements in building with composites. In *Polymer composites in the aerospace industry* (pp. 3–22). Elsevier. <https://doi.org/10.1016/B978-0-08-102679-3.00001-0>
- Sritharan, R., & Askari, D. (2021). *Interlaminar Properties Improvement of Nanocomposites Using Coiled Nanomaterials*. SAE Technical Paper. <https://doi.org/10.4271/2021-01-0027>
- Wang, Y., Gao, J., Ma, L., Ge, H., Zhu, G., & Zhu, Z. (2024). Full bio-based flame retardant towards multifunctional polylactic acid: Crystallization, flame retardant, antibacterial and enhanced mechanical properties. *International Journal of Biological Macromolecules*, 135891. <https://doi.org/10.1016/j.ijbiomac.2024.135891>
- Weitsman, Y. J., & Elahi, M. (2000). Effects of fluids on the deformation, strength and durability of polymeric composites—an overview. *Mechanics of Time-Dependent Materials*, 4, 107–126. <https://doi.org/10.1023/A:1009838128526>
- Zhang, K., Wang, F., Liang, W., Wang, Z., Duan, Z., & Yang, B. (2018). Thermal and mechanical properties of bamboo fiber reinforced epoxy composites. *Polymers*, 10(6), 608. <https://doi.org/10.3390/polym10060608>

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REDUCING RETURN RATES AND IMPROVING PRODUCT FIT THROUGH ADDITIVE MANUFACTURING

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Abstract

High product return rates create major financial, environmental, and reputational challenges for industries such as fashion, footwear, and medical devices. Many of these returns stem from poor product fit, design flaws, and unmet customer expectations. Additive Manufacturing (AM), or 3D printing, offers solutions through customization, prototyping, and reduced material waste. This paper explores how AM improves product quality and customer satisfaction, leading to lower return rates across multiple sectors. Challenges such as material limits, data accuracy, and lack of standardization are also discussed. Overall, AM shows strong potential to support sustainable manufacturing while reducing costs and building consumer trust.

Keywords: *Additive Manufacturing (AM); 3D Printing; Return Rates; Product Customization; Customer Satisfaction.*

1. Introduction

Today's market faces numerous challenges, such as high product return rates, poor product fit, design issues, and unmet customer preferences. According to Dirksen and Feldmann (2020), the high return rate causes financial losses due to reverse logistics, restocking, and disposal of returned products. Ford and Despeisse (2016) further argue that high return rates damage brand reputation in the long term. Indirectly, they also harm the environment by increasing waste accumulation and unnecessary transportation.

Additionally, financial losses have significant impacts on industries such as consumer goods, particularly fashion and footwear. These issues have raised growing concerns about sustainability and long-term business viability, especially for models reliant on high return rates. As noted by Delic et al. (2019), additive manufacturing (AM), or 3D printing, is an innovative process that produces products by adding material layer by layer based on digital models. It enables high precision and design flexibility. Unlike traditional subtractive methods, AM minimizes material waste and allows the creation of complex geometries. AM can also reduce return rates by enhancing product quality and enabling customization (ITG). Thomas and Gilbert (2014) state that AM provides an optimum solution by producing customized products that ensure precise fit and adaptability to customer preferences, thereby reducing return rates while maintaining design flexibility.

In AM, there are several strategies that can be employed to reduce return rates by improving customer satisfaction. The most significant include producing customized products for better fit, adopting made-to-order production, utilizing prototyping and product quality testing, reducing

waste, and implementing sustainable waste management practices.

The main objective of my paper is to investigate how AM can be used to reduce product return rates by improving customer satisfaction through better product quality, personalization, and sustainable practices. I focus on how AM helps address common issues such as poor product fit, design inconsistencies, and unmet consumer expectations, which are key drivers of returns. I also examine how the integration of 3D printing technologies contributes to waste reduction, rapid prototyping, and customization in industries such as fashion, footwear, and medical devices. At the same time, I highlight the challenges and limitations of AM including material constraints, post-processing, and data accuracy that still need to be resolved.

2. Literature Review

As reported by Dircksen and Feldmann (2020), product returns negatively impact businesses by influencing profitability, reducing operational efficiency, and damaging brand reputation. Delic et al. (2019) show that poor product fitness and a lack of customer satisfaction are key drivers of returns, especially in the fashion and furniture industries. Recent studies by Ford and Despeisse (2016) indicate that the most common reason for product returns is customer dissatisfaction, as consumers increasingly expect personalized shopping experiences. According to Verboeket and Krikke (2019), higher return rates can have a particularly significant effect on production flow by increasing logistics costs, complicating inventory management, and contributing to waste accumulation.

Many studies have investigated the causes of high product return rates and potential solutions. Kazmer et al. (2023) report that about 30% of returns in the clothing industry are due to improper sizing or color mismatches. Thomas and Gilbert (2014) noted that the footwear industry has successfully used AM technology to create customized, better-fitting shoes, thereby reducing returns. Similarly, Spalt and Bauernhansl (2016) found that 3D printing for personalized fit and design helps mitigate these challenges by providing consumers with products tailored to their needs.

According to Sun et al. (2022), AM addresses product returns by identifying and resolving issues at the design stage. In the medical device industry, AM has enabled the production of customized implants that match patient needs, significantly reducing return rates. Muir and Haddud (2018) reported that in the fashion and footwear sectors, 3D-printed prototypes were used to ensure better fit and function before mass production. Delic et al. (2019) emphasized that AM's capacity for customization across industries is increasingly viewed as a game changer in reducing returns.

Recent advances in 3D printing, materials science, and digital modeling have transformed the manufacture of personalized products. Kazmer et al. (2023) showed that new materials, which mimic the feel and durability of traditional products, allow manufacturers to create more durable, better-fitting items. Ford and Despeisse (2016) stated that digital modeling tools enable precise product adjustments based on customer data, improving satisfaction and reducing returns. According to Verboeket and Krikke (2019), as AM technology continues to evolve, it offers expanded opportunities for product customization and more effective industry development.

3. How AM Reduce Returns & Increase Customer Satisfaction

AM is playing an increasingly important role in making modern manufacturing more sustainable. By reducing waste through on-demand production and improving product quality with rapid prototyping, AM offers practical solutions that help companies minimize excess and operate more efficiently. The following sections highlight how these benefits are applied across industries to support both environmental goals and improved business outcomes.

3.1. Waste Reduction and Sustainable Manufacturing by Made-To-Order Manufacturing

AM technology provides the advantage of producing products on demand, reducing overproduction and the stockpiling of unsold items. It also offers flexibility by enabling companies to implement on-demand manufacturing strategies. According to Verboeket and Krikke (2019), this approach reduces large inventories, overproduction, and excess stock. Such a shift lowers storage and warehousing costs while helping businesses respond more quickly to changing market demands. By producing only what is needed, companies can operate more efficiently and with greater agility.

3.2. Prototyping & Product Quality Testing

Prototyping and rapid testing with AM is an effective way to reduce return rates. It helps catch problems such as poor fit before products reach customers. In the medical device industry, companies print functional prototypes to check design and fit before mass production, which lowers the risk of recalls or returns (Sun et al., 2022). AM also cuts waste by producing only what is needed. For example, IKEA used 3D printing to make personalized furniture, reducing excess material and improving efficiency reported by Ford & Despeisse (2016). Sun et al. (2022) also showed that AM decreases returns caused by defects or design inconsistencies. In footwear, as reported by Muir & Haddud (2018), companies use prototypes to test performance before large-scale production, ensuring better quality and fewer returns.

3.3. Customization

Manufacturers can use AM to produce customized products based on customers' personal measurements and preferences. Muir and Haddud (2018) showed how Adidas and Nike overcame challenges with product returns caused by sizing issues. Figure 1 shows Adidas' 3D-Printed Personalized Shoe as an example, where 3D printers were used to create perfectly fitting footwear. According to Thomas and Gilbert (2014), the use of AM for customizing shoe liners and structures has met customer expectations by delivering highly personalized products. Delic et al. (2019) also reported that in the fashion industry, 3D printing is used to produce on-demand clothing and footwear, ensuring that each product is tailored to customer requirements, thus reducing the likelihood of returns from poor fit or unsatisfactory design. According to Muir and Haddud (2018), one of the key benefits of AM is its ability to provide mass customization. Kazmer et al. (2023) added that this is achieved using digital modeling and 3D scanning, which enable the production of highly personalized products while minimizing sizing errors.



Figure 1. Adidas 3D-Printed Personalized Shoe

In the medical device industry, it is essential to produce highly customized products that meet individual patient needs. Companies use AM to manufacture personalized medical equipment and implants, such as custom knee replacements. By using medical data from patient scans, AM ensures a precise fit, reducing the risk of complications or the need for returns. Kazmer et al. (2023) stated that the accuracy provided by AM improves overall patient experience and satisfaction. Traditional manufacturing methods require additional tooling and rework to achieve this precision, which demands more time, labor, and cost. In contrast, AM enables rapid iteration and real-time modifications, ensuring products undergo fast and rigorous quality testing before reaching consumers.

3.4. Sustainable Material Utilization

One of the main advantages of AM is sustainability. AM allows precise control over material use, which helps reduce waste and makes production more efficient. Ford and Despeisse (2016) noted that this makes AM a cleaner alternative compared to traditional manufacturing. Delic et al. (2019) also showed that by enabling localized production, AM can reduce transportation, cut carbon emissions, and lower energy use. At the same time, AM improves product quality, reduces return rates, and increases customer satisfaction. With continued advances in 3D printing, AM will become an even more important part of modern manufacturing, supporting both efficiency and sustainability while staying focused on customer needs.

4. Impact Analysis: Applying AM to Improve Return Rates

This section evaluates how Additive Manufacturing (AM) impacts different industries focusing on the main dimension like fewer returns, products that meet requirements, and cost saving in long term. Tables and figures are used to summarize findings, with an emphasis on clear and consistent metrics.

4.1. Return Rate Reduction

Adoption in AM has shown significant reductions in product return rates as improving fit and customer satisfaction. For example, Zhou and Bernat (2024) reported that return rates in consumer product companies declined from 28% to 11.3% after integrating AM into design workflows. According to Xu (2023), Adidas reduced sneaker returns from 23% to 10.6% because of incorporating 3D-printed midsoles tailored to individual foot dimensions. In the medical industries, Align Technology (2023) reported that Invisalign aligners manufactured using AM required only 7% of adjustment requests compared to 32% for conventional orthodontics.

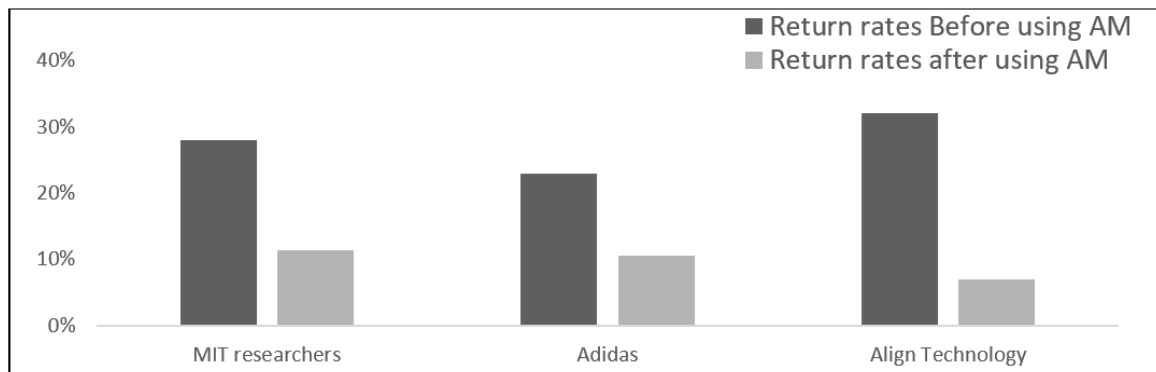


Figure 2. Reductions in Return Rates Across Industries

4.2. Comparative Industrial Impacts

AM benefits across various industries by increasing efficiency, precision, and customization. Table 1 represents case studies that demonstrate improvements in speed, quality, and return rate reduction. According to Gibson et al., 2021, Boeing achieved a 30–40% Reduction in aerospace components, while BMW reduced prototype development time by 30% as reported by Khajavi et al., 2014. Berman, 2012 showed that Nike leveraged AM to cut footwear returns by 35%, and Stryker produced patient-specific implants with 95% accuracy. HP reported a tenfold increase in production speed through AM as per Rayna and Striukova, 2016.

Table 1. Comparative Analysis of AM Impact Across Industries

Industry	Company Name	Key AM profit	Metric
Aerospace	Boeing	Weight reduction	30-40%
Automotive	BMW	Prototype speed	30% faster
Medical	Stryker	Custom implants	95% precision
Consumer	Nike	Return Rate	35% reduction
Electronics	HP	Production speed	10 times faster

5. Challenges and Limitations of AM

There are many challenges and limitations associated with AM, particularly in mass production. Producing customized products through AM is often not cost-effective or efficient at large scale. Industries must balance the benefits of customization with the costs of scaling AM for mass production, while also addressing both financial and technical constraints. Delic et al. (2019) noted that the high initial investment required for AM equipment and materials can be a major deterrent for many businesses. This section discusses some of the key limitations, including material constraints, consumer acceptance, and the complexities of integrating AI and data into AM workflows.

5.1. Material Constraints in AM

Material constraints are another significant limitation in AM. The range of materials available for AM is still narrower compared to traditional manufacturing methods. This is particularly challenging in the textile industry and in high-performance products. According to Gibson et al. (2021), the issue is especially critical in aerospace and biomedical fields, where materials must meet strict standards. Barman et al. (2024) highlighted that the textile industry struggles due to the lack of AM-compatible materials that can match traditional woven fabrics. Sun et al. (2022) noted that in sectors such as automotive and defense, materials must demonstrate high thermal stability, chemical resistance, and mechanical strength, but many of these requirements are still under development. Addressing these challenges will require advances in material science, nanotechnology, and hybrid AM processes.

5.2. Consumer Acceptance and Adoption

Although AM offers numerous advantages, many consumers remain hesitant to adopt

customized products or trust the technology. Ford and Despeisse (2016) noted that some consumers doubt the durability and quality of AM-produced items, making them reluctant to purchase such products. This hesitation often stems from familiarity with traditional manufacturing, which is perceived as superior in strength and longevity. Sun et al. (2022) emphasized that increasing awareness and demonstrating the reliability of AM components are essential steps for achieving long-term adoption.

5.3. Data and AI Integration Challenges

Another challenge is that AM requires large, high-quality datasets to train AI models effectively. A lack of standardized data limits the development of robust machine models. AM also demands high computational power, AI-driven simulations, and real-time monitoring capabilities. These requirements pose significant difficulties for small-scale manufacturers due to high initial costs and the need for specialized knowledge. Future advancements must address these challenges to reduce unnecessary overhead investments. Therefore, future research should focus on improving data interoperability, developing real-time adaptive AI models, and exploring novel materials compatible with AI-optimized AM processes.

5.4. Customization at mass scale

AM offers many advantages, such as the ability to create customized products tailored to individual needs. However, customization becomes challenging at the mass production level. Traditional manufacturing relies on standardized processes that produce efficient and predictable results, while AM requires specific materials and customized print and design settings. This complexity often leads to errors during design interpretation, file preparation, or production. AM also requires a robust digital network and skilled operators to manage unique CAD modeling. Since AM production is time-consuming, it can negatively impact customer satisfaction. Mellor et al., 2014 reported that mass personalization is also costly without efficient workflows and automation tools. To reduce return rates through better product fit, companies must ensure consistent quality across all products; otherwise, the benefits of customization may be outweighed by inconsistent quality.

5.5. Lack of Standardization in Fit Assessment

A key challenge in AM is the lack of standardized methods for ensuring proper sizing and comfort across diverse users. Thomas-Seale et al., 2018 noted that unlike traditional manufacturing, which benefits from established standards, AM focuses on individual customization, making consistency harder to achieve particularly in fields like prosthetics, eyewear, and personalized wearables. This often creates a gap between product fit and user expectations, leading to higher return rates. Developing fit standards tailored to AM would help ensure consistent quality and reduce mismatches.

5.6. Inaccurate or Incomplete Customer Input

To produce customized products, AM companies need accurate data, such as body measurements for garments and 3D scans for medical devices. Even minor inaccuracies can result in poor performance. The inability to provide accurate measurements due to a lack of tools and expertise often leads to incorrect data, which in turn produces low-quality outputs. For instance, taking body measurements at home can introduce inconsistencies caused by tape placement or posture. Similarly, home-use 3D scanners or mobile phone apps may generate incomplete or distorted geometry, especially in complex areas. Therefore, manufacturers need methods to validate and correct data to ensure customer needs are met and return rates are reduced. Furthermore, Gebler et al., 2014 noted that it is essential to establish systems for error-checking,

intuitive input tools, or guided scanning services to guarantee data accuracy

5.7. Post-Processing and Material Behavior

Even after ensuring accurate data and validating it, it is essential to account for post-processing steps such as sintering, curing, cooling, or surface finishing. These processes may introduce minor defects that can have a significant impact on product quality. For example, polymer-based parts produced through FDM or SLA printing often shrink during cooling or curing. Similarly, metals printed via powder bed fusion may warp due to residual thermal stress, altering critical dimensions. Such changes can cause discomfort and functional issues, especially in medical devices. Ngo et al., 2018 mentioned that manufacturers need to identify material behavior by studying its properties to determine the optimum conditions for specific printing processes. However, research in this area is still ongoing. Inconsistent post-processing also affects surface finish, which influences the user's perception of fit and comfort., to improve accuracy and reduce returns, more precise simulation and monitoring of material behavior throughout the AM process are necessary.

5.8. Consumer Perception and Expectation Management

Products may be returned not only because of poor fit but also due to unmet customer expectations. This is often tied to personal preferences such as texture, color, weight, or overall "feel." Low-cost or rapid AM processes can produce visible layer lines, inconsistent finishes, or unexpected material properties. Consumers, however, may expect smooth, polished products like injection-molded items. In addition, online buyers may not fully understand the look or tactile qualities of a product, which can lead to disappointment upon delivery. This issue is particularly common with personalized products, where returns are difficult or impossible to resell. Therefore, Jin et al., 2017 noted that, clear communication about material characteristics, finish options, and aesthetic outcomes are essential. Providing samples, 3D previews, or even haptic feedback simulations can help align customer expectations. Effective expectation management, supported by realistic marketing and post-sale service, can significantly reduce unnecessary returns and improve customer satisfaction.

6. Conclusion

High return rates in sectors such as fashion, footwear, and medical devices continue to generate financial losses, environmental burdens, and reputational risks. Evidence shows that poor product fit and unmet customer expectations remain the primary causes of these returns. Additive Manufacturing (AM) offers a promising pathway forward by enabling flexible design, product customization, and waste reduction. Through the production of personalized items, AM not only improves product quality but also enhances customer satisfaction and reduces return rates. The integration of digital modeling further strengthens fitting accuracy and lowers logistics costs. Despite these advantages, challenges with materials, standardization, and data accuracy still limit widespread adoption and require further investigation. Overall, AM represents a significant step toward more sustainable, efficient, and consumer-focused manufacturing. Future research should prioritize the development of standardized fit assessment methods tailored to AM, ensuring consistency, reducing mismatches, and ultimately minimizing product returns.

7. Disclaimer Statements

Funding: None

Conflict of Interest: None

8. References

- Adidas. (n.d.). Adidas Futurecraft 4D printed shoe [Image].
<https://www.materialise.com/en/inspiration/cases/adidas-futurecraft-3d-printed-personalized-shoe>.
- Align Technology. (2023). *Invisalign: Innovation in orthodontics*. <https://www.aligntech.com>
- Alsing, D. (2024). Evaluating and Managing Post-Pandemic Consumer-Packaged Goods Supply Chain Resilience Through a Risk Analysis and Mitigation Lens. George Washington University.
https://scholarspace.library.gwu.edu/concern/gw_etds/br86b434w
- Barman, N. K., Bhattacharya, S. S., & Alagirusamy, R. (2024). Textile structures in concrete reinforcement. *Textile Progress*, 56(1), 1-229. <https://doi.org/10.1080/00405167.2023.2266930>
- Berman, B. (2012). 3-D printing: The new industrial revolution. *Business Horizons*, 55(2), 155-162.
<https://doi.org/10.1016/j.bushor.2011.11.003>
- Delic, M., Eysers, D. R., & Mikulic, J. (2019). Additive manufacturing: empirical evidence for supply chain integration and performance from the automotive industry. *Supply Chain Management: An International Journal*, 24(5), 604-621. <https://doi.org/10.1108/SCM-12-2017-0406>
- Dirksen, M., & Feldmann, C. (2020). Holistic evaluation of the impacts of additive manufacturing on sustainability, distribution costs, and time in global supply chains. *Transportation Research Procedia*, 48, 2140-2165. <https://doi.org/10.1016/j.trpro.2020.08.272>
- Ford, S., & Despeisse, M. (2016). Additive manufacturing and sustainability: an exploratory study of the advantages and challenges. *Journal of cleaner Production*, 137, 1573-1587.
<https://doi.org/10.1016/j.jclepro.2016.04.150>
- Gebler, M., Uiterkamp, A. J. S., & Visser, C. (2014). A global sustainability perspective on 3D printing technologies. *Energy policy*, 74, 158-167. <https://doi.org/10.1016/j.enpol.2014.08.033>
- Gibson, I., Rosen, D., Stucker, B., Khorasani, M., Rosen, D., Stucker, B., & Khorasani, M. (2021). Additive manufacturing technologies (Vol. 17, pp. 160-186). Cham, Switzerland: Springer.
<https://doi.org/10.1007/978-3-030-56127-7>
- Jin, Y., Li, X., Campbell, R. I., & Ji, S. (2018). Visualizing the hotspots and emerging trends of 3D printing through scientometrics. *Rapid Prototyping Journal*, 24(5), 801-812. <https://doi.org/10.1108/RPJ-05-2017-0100>
- Kazmer, D., Peterson, A. M., Masato, D., Colon, A. R., & Krantz, J. (2023). Strategic cost and sustainability analyses of injection molding and material extrusion additive manufacturing. *Polymer Engineering & Science*, 63(3), 943-958. <https://doi.org/10.1002/pen.26256>
- Khajavi, S. H., Partanen, J., & Holmström, J. (2014). Additive manufacturing in the spare parts supply chain. *Computers in industry*, 65(1), 50-63. <https://doi.org/10.1016/j.compind.2013.07.008>
- Mancebo, C. P. C. (2023). 3D printing and its possible role in the sustainability of the fashion market (Master's thesis, Universidade da Beira Interior (Portugal)).
<https://core.ac.uk/download/pdf/599045660.pdf>
- Mellor, S., Hao, L., & Zhang, D. (2014). Additive manufacturing: A framework for implementation. *International journal of production economics*, 149, 194-201.
<https://doi.org/10.1016/j.ijpe.2013.07.008>
- Muir, M., & Haddud, A. (2018). Additive manufacturing in the mechanical engineering and medical industries spare parts supply chain. *Journal of Manufacturing Technology Management*, 29(2), 372-397. <https://doi.org/10.1108/JMTM-01-2017-0004>
- Ngo, T. D., Kashani, A., Imbalzano, G., Nguyen, K. T., & Hui, D. (2018). Additive manufacturing (3D printing): A review of materials, methods, applications and challenges. *Composites Part B: Engineering*, 143, 172-196. <https://doi.org/10.1016/j.compositesb.2018.02.012>
- Rayna, T., & Striukova, L. (2016). From rapid prototyping to home fabrication: How 3D printing is changing business model innovation. *Technological forecasting and social change*, 102, 214-224.
<https://doi.org/10.1016/j.techfore.2015.07.023>
- Sonova. (2024). *Annual Report 2023/24*. Sonova Holding AG.
https://www.sonova.com/sites/default/files/2024-05/01_Sonova_AR_23-24_Full_Report_en.pdf
- Spalt, P., & Bauernhansl, T. (2016). A framework for the integration of additive manufacturing technologies

- in production networks. *Procedia CIRP*, 57, 716-721. <https://doi.org/10.1016/j.procir.2016.11.124>
- Sun, Z., Ma, Y., Ponge, D., Zaefferer, S., Jäggle, E. A., Gault, B., ... & Raabe, D. (2022). Thermodynamics-guided alloy and process design for additive manufacturing. *Nature communications*, 13(1), 4361.
- Thomas, D. S., & Gilbert, S. W. (2014). Costs and cost effectiveness of additive manufacturing. NIST special publication, 1176, 12. <http://dx.doi.org/10.6028/NIST.SP.1176>
- Thomas-Seale, L. E., Kirkman-Brown, J. C., Attallah, M. M., Espino, D. M., & Shepherd, D. E. (2018). The barriers to the progression of additive manufacture: Perspectives from UK industry. *International Journal of Production Economics*, 198, 104-118. <https://doi.org/10.1016/j.ijpe.2018.02.003>
- Verboeket, V., & Krikke, H. (2019). The disruptive impact of additive manufacturing on supply chains: A literature study, conceptual framework and research agenda. *Computers in Industry*, 111, 91-107. <https://doi.org/10.1016/j.compind.2019.07.003>
- Xu, J. (2023). Sustainable practices in the supply chain of the fashion industry: the cases of Nike, Adidas, and Puma (Doctoral dissertation, European University Institute). Available at: <https://cadmus.eui.eu/handle/1814/7ee3f899-e8bc-5b3a-b88c-bdded104540f>
- Zhou, L., Miller, J., Vezza, J., Mayster, M., Raffay, M., Justice, Q., ... & Bernat, J. (2024). Additive manufacturing: a comprehensive review. *Sensors*, 24(9), 2668. <https://doi.org/10.3390/s24092668>

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NEXT GENERATION IN-SITU RESOURCE UTILIZATION PILOT EXCAVATOR CONTROL ROOM & FACILITY DESIGN

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Abstract

This study focused on identifying recommendations for designing the Next Generation In-Situ Resource Utilization (ISRU) Pilot Excavator (IPEX) control room and facility. This research highlights opportunities for incremental improvements across the control room's design, processes, and amenities, fostering a more efficient and supportive environment for the IPEX team. Participants consisted of IPEX control room operators who were recruited and interviewed; this resulted in 50 recommendations from the 33 open-ended questions asked of the eight participants. Spradley's domain analysis was used to code and analyze the open-ended question responses within 11 domains consisting of design considerations for IPEX displays, room layout, individual desk layout, lighting, shiftwork, shift changeover, control room employee interaction, control room environment, workload, rest area and breaks, and food area. Researchers employed an interview methodology. Spradley's domain analysis was used to identify and further partition themes into sections called "Cover Terms." These terms, or themes, were organized further into sub-themes called "Included Terms" for each of the 11 domains. The study implications and future research are also addressed.

Keywords: *Autonomous Systems; Control Room; Display Design; Lighting; Shiftwork; Space; Spradley's Domain Analysis; Workload.*

1. Introduction

This study focused on identifying recommendations for designing the Next Generation In-Situ Resource Utilization (ISRU) Pilot Excavator (IPEX) control room and facility. The ISRU IPEX is a groundbreaking robotic system designed by NASA to revolutionize lunar exploration. It resembles an excavator and dump truck used to mine and transport lunar regolith. Regolith is a granular material on the Moon's surface that contains resources such as oxygen, water ice, metals, and volatiles (Sanders, 2018). IPEX is designed for a future lunar technology demonstration mission of 11 days with constant robotic operations. It will be a high-paced mission that requires focused and responsive ground controllers to make rapid, informed decisions. This study supports that goal by identifying areas of improvement for the IPEX control room and facility through interviewing control room operators working within a 5-day mock IPEX mission in the fall of 2024. During that mock mission, operators worked 13-hour shifts daily for 5 days. Each shift had two crews, with operators rotating out every two hours during the 13-hour shift. The first and last hour of each shift overlapped with the incoming shifts. Therefore, there were four crews, two working half of each 13-hour shift. This research highlights opportunities for incremental improvements across the control room's design, processes, and amenities, fostering a more efficient and supportive environment for the IPEX

team. Participants consisted of IPEx control room operators who were recruited and interviewed; this resulted in 50 recommendations from the 33 open-ended questions asked of the eight participants. Spradley's domain analysis was used to code and analyze the open-ended question responses within 11 domains consisting of design considerations for IPEx displays, room layout, individual desk layout, lighting, shiftwork, shift changeover, control room employee interaction, control room environment, workload, rest area & breaks, and food area.

The IPEx operators were selected based on their background and filled four roles: Primary Operator, Secondary Operator, Telemetry Desk, and Simulation Coordinator. The Primary Operator is the decision authority responsible for sending commands from the control room to IPEx. The Secondary Operator assisted the Primary Operator in planning the commands and reviewing telemetry. The Telemetry Desk downlinked data from IPEx, prepared it for review, and monitored for changing trends. The Simulation Coordinator (or Sim-C) was a role specific to the mock mission that monitored the operators, real-time telemetry, and situational camera views from inside the test area. The Sim-C recorded data on what the operators (with their limited data) thought was happening in the mission versus what was happening. This data was used to identify opportunities for improving user interfaces and data products to inform operators better. As this was the first IPEx mock mission, primary operators with extensive user interface experience were selected from the IPEx software development team. Secondary Operators and Telemetry Desk were a mixture of full-time and part-time IPEx engineers, and some with little IPEx experience. This mixture provided feedback from a variety of experiences and perspectives. The Sim-Cs were IPEx leads and Systems Engineers.

2. Literature Review

This section consists of literature on IPEx, IPEx missions, and supervised autonomous operations. IPEx is a robotic excavator designed for operations on planetary bodies with reduced gravity (Schuler et al., 2024). The Moon has gravity levels approximately 1/6th and Mars 1/3rd of those on Earth, which results in lower weight and traction for vehicles operating on their surfaces (Heiken et al., 1991). On Earth, the weight of an excavator is its primary method of reacting to the forces of digging. Lower weight equates to lower ability to push a blade into the ground and collect material. Additionally, the cost of launching equipment to space is high. As of 2023, the cost to send 1kg to the moon was \$1.2 million (Gormly, 2023). Therefore, excavators for future missions to the Moon and Mars must be low mass. However, this will exacerbate their difficulty producing enough reaction force to excavate.

IPEx solves this problem by eliminating weight and traction as the primary method of reacting to excavation forces. It does this by implementing dual excavation tools, known as bucket drums, that dig simultaneously but in opposing directions. The bucket drums react off one another instead of the vehicle's traction, enabling excavation in reduced gravity with low mass systems (Mueller, 2016). This concept began in 2010 and has gradually progressed through NASA's technology readiness levels (TRL) (NASA Office of the Chief Technologist, 2020). IPEx is currently at a TRL of 5, meaning a Brassboard IPEx system has been validated in a relevant environment. The development of TRL 6 is underway, which will result in a flight-ready system that can be sent to the moon to demonstrate its function in the actual lunar environment (resulting in TRL 7).

The notional IPEx technology demonstration mission would only last 11 days on the lunar surface. At most locations on the moon, there are 14 days of continuous daylight followed by 14 days of darkness (Heiken et al., 1991). The "lunar night" is costly to survive due to extreme temperatures, which is beyond the scope of an IPEx technology demonstration mission. During the 11-day mission,

IPEX will demonstrate excavation and transportation of up to 10,000 kg of lunar regolith. To meet that goal, IPEX must be operated at a high rate. “Joy-sticking” IPEX from Earth is not possible due to the time delays between the control room and the robot on the moon (~14 seconds round trip) (Buckles, 2022). Sun et al. (2023) discuss what autonomy on Mars currently enables, such as AutoNav, long autonomous drives, and onboard science targeting. Walker et al. (2024) suggest how to design control rooms and interfaces to maximize effective supervision of autonomous systems by human operators. IPEX uses a “supervised autonomous” operation mode to accommodate this operational lag, where controllers send a series of high-level tasks that IPEX executes independently (Cloud, 2025). The tasks start as simple, short drives, and once the operational area is mapped, the tasks become more complex and longer. If IPEX encounters an anomaly at any point, it stops and awaits direction from the controllers. The IPEX control room must support this fast-paced mission profile to meet the mission objectives. The short-duration mission means that IPEX must have its concept of operations (CONOPS) clearly outlined in all contingency plans. Performing simulated missions on Earth, such as the one discussed here, helps the team identify areas for improvement and streamline future mission operations.

3. Methodology

The current study employed a qualitative research methodology, specifically, phenomenology, which was appropriate because the primary purpose was “to describe the essence of a lived phenomenon” (Creswell, 2013, pp. 104–105). In the context of the current study, this “lived phenomenon” was control operators working during a 5-day mock IPEX mission. The data collection approach was interviews. The data was used to identify recommendation improvement ideas for the Next Generation control room and facility design. Participants were recruited through email using convenience sampling, which involved selecting individuals who were readily available and willing to participate. Eight participants provided consent to participate in the interview. As this was voluntary, interview participants were instructed to stop participating at any time without penalty.

Spradley’s (2016) domain analysis was used to identify themes from the data collected from the 33 questions asked of interview participants. The rationale behind the specific questions was to gain an understanding of strengths, weaknesses, and opportunities for improvement within the 11 domains of design considerations for IPEX displays, room layout, individual desk layout, lighting, shiftwork, shift changeover, control room employee interaction, control room environment, workload, rest area and breaks, and food area. Researchers employed an interview methodology. Domain analysis is a qualitative research method used to identify and categorize cultural themes or patterns within a specific context. The selection of domain analysis for this purpose is due to its effectiveness in uncovering meaningful categories and relationships within the qualitative data. Spradley’s (2016) domain analysis was used to determine common themes and conjectures from domains referred to as cover terms. Then, the cover terms, or themes, were organized further into sub-themes, “Included Terms,” determined from participants’ responses. Standards of rigor in qualitative research, validity and reliability (Creswell, 2013), credibility and transferability (Ary et al., 2010), were followed and addressed.

4. Results

The data analysis was conducted in two stages. The first stage of the analysis consisted of reviewing the participants’ written responses to see if they were commensurate with the research questions. The second stage of the research consisted of identifying similar comments, common patterns, and themes. The interview findings resulted in 50 recommendations based on the data collected from the 33 open-ended questions asked of the eight participants, who were IPEX control

room operators. Spradley's (2016) domain analysis was used to code and analyze the open-ended question responses within 11 domains (see Tables 1 - 11). Each table contains one domain, cover term(s), included term(s), and conjectures. The 11 domains consist of design considerations for IPEx displays, room layout, individual desk layout, lighting, shiftwork, shift changeover, control room employee interaction, control room environment, workload, rest area & breaks, and food area. Within the 11 major domains, the data was further partitioned into "Cover Terms." These "Cover Terms" were further partitioned into "Included Terms." Examples from the respondents within different categories are discussed using P1 through P8 to depict the eight interview participants. After the cover and included terms are identified, conclusions can be drawn about recommendations to enhance the control room and the facility that houses the control room, which are later discussed in the recommendation section.

Domain 1: Domain 1 is "IPEx Control Room Operator's Design Considerations of Displays" (see Table 1). Two cover terms were identified: "Observation" and "Recommendations." There was no included term for the "Observation" cover term. Within the "Recommendations" cover term, the included term was "Usability." Domain 1 corresponded to research questions (RQs) on the preliminary design of the displays regarding access and interoperation of critical information, and how to make the Next Generation display layout more intuitive.

Within the "Observation" sub-theme, interview participants described their observations of menu navigation, zooming/adjusting camera views, and font size. Examples regarding menu navigation include P3 stated, "drill down capability is slow," P4 stated, "operator cognitive load can be high," P5 stated, "push a lot of buttons to get the information needed," and P7 stated, "some menus illegible, dropdown menu not readable...cognitive overload in clicking on many things for an action." Examples with regards to zooming/adjusting camera views include, P1 stated, "Live camera views on the middle screen...need one to three views at a time might be better than the six currently displayed," P2 stated, "A lot of cameras are not pertinent, so display the pertinent ones," and P6 stated, "less intuitive is the part in displaying cameras." Examples regarding font size include, P4 stated, "displays could have larger font," P7 stated, "some fonts illegible," and P8 stated, "font size small makes it hard to look at a glance to get quick information."

Within the "Usability" sub-theme, interview participants described their observations that occurred with the graphical user interface (GUI) as P1 stated, "some features would be useful, such as warnings, errors, and informational messages," P4 stated, "want a more clean display because there are a lot of buttons/entry buttons stacked together...scripts/macros could do some of the repeatable tasks versus performed manually by operators...improve understanding of whether image is recent (did cam go offline) so a timeout has a green border then 20 seconds maybe turn yellow or over a minute it is red. Timestamp but problem to enforce reading of small print," P5 stated, "better to have one big display in the room to know what the robot is doing," and P7 stated, "computer monitor to control displays from one computer on the operator's desk prior to displaying it on big displays."

Within the "Usability" sub-theme, interview participants described their observations that occurred with the camera feeds as P1 stated, "would be good to help troubleshoot issues if able to filter on robot camera software," P3 stated, "might be nice to have virtual reality (VR) for a look around capability of various views," P4 stated, "Camera feeds displayed in a grid layout and one can be blown up in size but can be tedious, interface could be made easier to make a camera feed full screen or zoom in on the feed and adjust exposure (brighten/darken)," and P5 stated, "Situational Awareness (SA) camera exists in testbed but not on the moon...SA camera is key to understanding the context of the data."

Table 1. Domain 1

Domain 1: IPEX Control Room Operators' Design Considerations of Displays			
Domain 1	Cover Term	Included Term	Conjectures
Displays	Observation	--	1.1 Menu navigation. 1.2 Zooming/adjusting camera views. 1.3 Font size.
	Recommendations	Usability	1.4 GUI. 1.5 Camera feeds.

Domain 2: Domain 2 is "IPEX Control Room Operator's Design Considerations of Room Layout" (see Table 2). Two cover terms were identified: "Observation" and "Recommendations." There was no included term for the "Observation" cover term. Within the "Recommendation" cover term, the included terms were "Accessories" and "Physical Space." Domain 2 corresponded to RQs on the room layout regarding obstacles and inefficiencies that hinder team communications, access to shared resources (i.e., printers, whiteboards, reference materials), and suggestions for improvement.

Within the "Observation" cover term, interview participants described their observations with cables, whiteboard, printer, and tours. Examples regarding cable management include P6 stated, "longer extension cords," and P8 stated, "cables near display." Examples regarding the whiteboard include, P1 stated, "whiteboard is electronic...anyone in the room can scribble on it," and P8 stated, "Digital whiteboard is sufficient." Examples regarding a printer include: P1 stated, "Could print screen for later, but printer would be useful," P2 stated, "printer down the hall," and P8 stated, "printer access is good." Examples regarding tours include P7 stated, "tours were distracting," and P3 stated, "challenges when observers are present."

Within the "Recommendation" cover term under the "accessories" included term, interview participants described their recommendations within the control room. For example, P1 stated, "put whiteboard on wheels so that it could be moved within the control room...color printer in the control room would be useful for graphs," and P6 stated, "longer extension cords so the desk would not need to be close to the wall." As for recommendations on a status visual, P5 stated, "Counting number of laps is manually updated, counter for number of laps was on the other side of room (easy to forget about it)," and P8 stated, "Indicator showing where we are in mission concept of operations (track reps but need counter also for laps). Status Visual on where we are in the cycle."

Within the "Recommendation" cover term under the "physical space" included term, interview participants described their recommendations for the room layout. For example, regarding interaction, P3 stated, "making sure there was enough walking space...can be tight when there are observers," and P5 stated, "Far side of the room was more difficult to interact with other operators." For example, regarding tours, P3 stated, "Observation behind glass would be helpful," and P7 stated, "Observation without distraction is needed."

Table 2. Domain 2

Domain 2: IPEX Control Room Operators' Design Considerations on Room Layout			
Domain 2	Cover Term	Included Term	Conjectures
Room Layout	Observation	--	2.1 Cable management. 2.2 Whiteboard. 2.3 Printer. 2.4 Tours.
	Recommendations	Accessories	2.5 Whiteboard on wheels. 2.6 Printer in the control room. 2.7 Longer extension cords. 2.8 Status Visual (where we are in a cycle).
		Physical Space	2.9 Interaction. 2.10 Tours.

Domain 3: Domain 3 is "IPEX Control Room Operator's Design Considerations of Individual Desk Layout" (see Table 3). Two cover terms were identified: "Observation" and "Recommendations." There was no included term for the "Observation" cover term. Within the "Recommendation" cover term, the included terms were "Desk" and "Accessories." Domain 3 corresponded to RQs on the individual desk layout regarding comfort of workstations in terms of ergonomics, level of support for effective multitasking, and improvement recommendations.

Within the "Observation" cover term, interview participants described their observations of their individual desk layout, consisting of chairs and desks. Examples regarding chairs include P1 stated, "Chairs are great," and P2 stated, "good," and P6 stated, "The chair is adjustable." Examples regarding desks include P3 stated, "workstation works well," P5 stated, "state of art furniture including standup desks – had balance board so moving and is healthy," P6 stated, standing desks were great – liked adjustable height," and P7 stated, "desk space is large enough."

Within the "Recommendation" cover term under the "Desk" included term, interview participants described their recommendations for the control room. For example, P1 stated, "Motorized desks should be adjustable," and P3 stated, "Make sure there is enough walking space between desks to interact with team members."

Within the "Recommendation" cover term under the "Accessories" included term, interview participants described their recommendations for the individual desk layout. For example, P1 stated, "balance boards...can stand on them to keep body from tightening up...standing desks could have portable treadmills to walk while working," P3 stated, "balance boards were useful...maybe have more available," P6 stated, "stress balls could help during low workload," and P8 stated, "consider having adapters so plug-in – some desks had a cup holder but all should have it. Also, an eBoard (USB-C generic docking station/mouse plug in for laptop (keyboard trays)."

Table 3. Domain 3

Domain 3: IPEX Control Room Operators' Design Considerations on Individual Desk Layout			
Domain 3	Cover Term	Included Term	Conjectures
Individual Desk Layout	Observation	--	3.1 Chairs. 3.2 Desks.
		Desk	3.3 Desk adjustability. 3.4 Desk spacing.
	Recommendations	Accessories	3.5 Balance Board/Treadmill. 3.6 Desk accessories (i.e., stress balls, cup holders, and adapters). 3.7 Adapters

Domain 4: Domain 4 is "IPEX Control Room Operator's Design Considerations of Lighting" (see Table 4). Two cover terms were identified: "Observation" and "Recommendations." The "Observation" cover term has two included terms, consisting of "Functionality" and "Glare." There was no included term for the "Recommendation" cover term. Domain 4 corresponded to RQs on lighting regarding description of control room lighting (i.e., suitability for sustained monitoring tasks, glare, difficulty transitioning between different lighting levels) and improvement ideas (i.e., task-specific lighting improves experience).

Within the "Observation" cover term, interview participants described their observations on control room lighting regarding functionality and glare. Examples regarding lighting with regards to functionality include P3 stated, "good as is," P6 stated, "works well to avoid headaches," and P7 stated, "testing times lights were on so just an adjustment at first and helped with focus." Examples regarding observations on glare include, P2 stated, "Lighting good – no glare," and P7 stated, "Window has blinds/curtains, maybe, so no glare because outer lighting did not impact...larger window would maybe be distracting."

Within the "Recommendation" cover term, interview participants described their recommendations for the control room. For example, P1 stated, "Lights on could cause eye fatigue – maybe needs them on sometimes – not sure how everyone feels on this. Maybe sufficient with room window," and P6 stated, "Could explore dim lights within the room and in the rest of the building to avoid adjusting from different lighting levels," P5 stated, "more local lighting that could be turned on/off on each desk," and P7 stated, "helpful to have a 7-segment display clock using an old computer monitor for a clock."

Table 4. Domain 4

Domain 4: IPEX Control Room Operators' Design Considerations on Lighting			
Domain 4	Cover Term	Included Term	Conjectures
Lighting	Observation	Functionality	4.1 Appropriate lighting. 4.2 Desks
		Glare	4.3 Nonexistent.
	Recommendations	--	4.4 Lighting level 4.5 Lighting from other sources (i.e., window, clock)

Domain 5: Domain 5 is “IPEX Control Room Operator’s Design Considerations of Shiftwork” (see Table 5). Two cover terms were identified: “Observation” and “Recommendations.” Within the “Observation” cover term, the included terms were “Positives” and “Challenges.” There was no included term for the “Recommendation” cover term. Domain 5 corresponded to RQs on the shiftwork regarding how participants liked working a 13-hour day, impact, if any, on performance, and recommendations (i.e., reduce fatigue or stress, shift lengths and rotations).

Within the “Observation” cover term, interview participants described their observations on the positives and challenges of shiftwork. Examples regarding positives of shiftwork include P2 stated, “Liked it/perfect,” P3 stated, “Worked well. I just did a different one with a four-shift rotation. There was too much turnover, it was hard to get volunteers, and the schedule broke down. Two shifts have lots of good consistency (of staff),” and P6 stated, “Given the format of the concept of operations, it worked well. Three shifts could be more difficult in the mock missions.” Examples regarding challenges of shiftwork include P1 stated, “5 days was doable but hard on families and self. So, being more extended would be even more challenging,” and P6 stated, “Sustainable for a week maximum. Night shift affects your body.”

Within the “Recommendation” cover term, interview participants described their recommendations on shiftwork. For example, P1 stated, “So, possibly three shifts may be more appropriate – less stress on body/brain,” P3 stated, “Not for day shift. May suggest for night shift to be a three/four hour shifts and have a room with cots or air mattresses to get some sleep to alleviate fatigue,” P6 stated, “designated rest areas with blankets for the 5-day mock missions. For future/longer missions, different scenario needs to be explored pending schedules, life, etc.,” P7 stated, “Two 13 hour shifts with 3-60 minutes overlap – possibly three shifts are better and to cycle off after eight hours with four hours of overlap,” and P8 stated, “Possibly try three shifts to see pros/cons.”

Table 5. Domain 5

<i>Domain 5: IPEX Control Room Operators’ Design Considerations on Shiftwork</i>			
Domain 5	Cover Term	Included Term	Conjectures
Shiftwork	Observation	Strengths	5.1 Two shifts work well. 5.2 Consistency of staff.
		Challenges	5.3 Hard on families. 5.4 Night shift affects your body.
	Recommendations	--	5.5 Three shifts. 5.6 Four hours of overlap. 5.7 Rest area

Domain 6: Domain 6 is “IPEX Control Room Operator’s Design Considerations of Shift Changeover” (see Table 6). Two cover terms were identified: “Observation” and “Recommendations.” There were no included terms for either cover term. Domain 6 corresponded to RQs on the shift changeover regarding how effective the process is for transitioning between shifts, potential gaps in communication, vital information needed to be passed to the next shift for seamless changeovers, and any issues with incomplete or unclear information at handovers.

Within the “Observation” cover term, interview participants described their observations on the shift changeover. Examples of observations of shift changeover include P1 stated, “Share trends,” P2 stated, “Good,” P3 stated, “Liked having the 24 call in number live to keep up to date – Teams or call in to listen in on drive in and out which improved info transfer,” and P6 stated, “More

information exchanged if something bad happened...robot did not break but did a lot of prep work in case there were issues but information passed over easily.”

Within the “Recommendation” cover term, interview participants described their recommendations on shift changeover. For example, P1 stated, “More efficient to show graphs...checklists could be used,” P5 stated, “Need briefing for new shift for big picture on what happened that morning or prior shift. 1. Big picture 2. Focus on the job...needed training prior to know which screen...GUI was not easy to get information to give during handovers,” P6 stated, “Checklist could be useful,” P7 stated, “New and not developed procedure for handover, which should cover a). sitting down to get acclimated, b). shift to share the encountered challenge and what was being done to mitigate it, and c). streamline way to do that,” and P8 stated, “room for improvement. Data (i.e., telemetry, snippets of video, etc.) would be good to share as a note so it could be pulled up versus told (show instead of tell). Interfaces to pull up past noteworthy events. Checklists for how different things went.”

Table 6. Domain 6

<i>Domain 6: IPEX Control Room Operators’ Design Considerations on Shift Changeover</i>			
Domain 6	Cover Term	Included Term	Conjectures
Shift Changeover	Observation	--	6.1 Type of content shared. 6.2 Mode used when sharing content.
	Recommendations	--	6.3 Checklists. 6.4 Training on GUI screens. 6.5 Briefing for new shift. 6.6 Formal handover procedure. 6.7 Data to share (i.e., video, telemetry, etc.)

Domain 7: Domain 7 is “IPEX Control Room Operator’s Design Considerations of Control Room Employee Interaction” (see Table 7). Two cover terms were identified: “Observation” and “Recommendations.” Within the “Observation” cover term, the included terms were “General” and “Tours.” There was no included term for the “Recommendation” cover term. Domain 7 corresponded to RQs on control room employee interaction regarding barriers (i.e., physical, procedural, cultural) to effective teamwork and improvement ideas to enhance communications during mission control operations.

Within the “Observation” cover term, interview participants described their observations on general operations and operations when tours were present with regard to control room employee interaction. Examples regarding general operations of control room employee interaction include P3 stated, “Team worked well together,” P5 stated, “Understand when to be formal/informal...great culture but times where operators need to be more disciplined,” P6 stated, “Easy to communicate...no barriers to effective teamwork,” and P8 stated, “Easy to jump from one work station to the next. Used whiteboard to sketch things out.” Examples regarding when tours were present in the control room employee interaction include P7 stated, “strange when others in the room are external (tours) to the team,” and P8 stated, “Tours mainly have a low impact as long as they are not in a critical operation. Tight space.”

Within the “Recommendation” cover term, interview participants described their recommendations on control room employee interaction. For example, P1 stated, “Mission control type role, designated a backup driver, would sit in a chair behind other desks to lead the team. If

procedure, he/she would have been marking off checklist, let us make sure all on same page before sending command and making sure risk level okay,” P3 stated, “Test conductor role to address any barriers and facilitate conversations,” and P5 stated, “Need briefing at beginning and end of shifts and could walk over to talk to other operators.”

Table 7. Domain 7

Domain 7: IPEX Control Room Operators’ Design Considerations on Control Room Employee Interaction

Domain 7	Cover Term	Included Term	Conjectures
Control Room Employee Interaction	Observation	General	7.1 Effective teams. 7.2 Team culture.
		Tours	7.3 Internal team members' view of visitors. 7.4 Tours' impact during critical operations.
	Recommendations	--	7.5 Team leader role. 7.6 Briefings.

Domain 8: Domain 8 is “IPEX Control Room Operator’s Design Considerations of Control Room Environment” (see Table 8). Two cover terms were identified: “Observation” and “Recommendations.” Within the “Observation” cover term, the included terms were “Temperature” and “Other.” There was no included term for the “Recommendation” cover term. Domain 8 corresponded to RQs on the control room environment regarding temperature, ventilation, or noise levels impacting ability to focus, distractions or disruptions, or suggestions for improving the physical environment.

Within the “Observation” cover term under the “Temperature” or “Other” included terms, interview participants described their observations of the control room environment. Examples regarding control room environment observations regarding temperature include P1 stated, “temperature hard due to individual differences,” and P5 stated, “Need to be able to adjust temperature.” Examples regarding control room environment observations regarding others include P1 stated, “Dark room kept people calm...cabin fever,” and P3 stated, “hectic during changeovers/visitors.”

Within the “Recommendation” cover term, interview participants described their recommendations on the control room environment. For example, P3 stated, “Glass staging area where visitors/shift changeover conversations could occur,” P6 stated, “Safety may not allow it, but maybe desk heaters/fans,” and P8 stated, “Want more inspirational wall graphics.”

Table 8. Domain 8

Domain 8: IPEX Control Room Operators' Design Considerations on Control Room Environment			
Domain 8	Cover Term	Included Term	Conjectures
Control Room Environment	Observation	Temperature	8.1 Individual differences. 8.2 Ability to adjust temperature.
		Other	8.3 Perception of a dark room. 8.4 Perception of changeovers/visitors.
		Recommendations	8.5 Area for changeovers/visitors. 8.6 Desk heaters/fans. 8.7 Inspirational wall décor.
	Recommendations	--	

Domain 9: Domain 9 is "IPEX Control Room Operator's Design Considerations of Workload" (see Table 9). Two cover terms were identified: "Observation" and "Recommendations." Within the "Observation" cover term, the included terms were "General" and "Alertness." There was no included term for the "Recommendation" cover term. Domain 9 corresponds to RQs on workload regarding how to combat periods within the shift where there is little to monitor, strategies used to stay engaged as lessons learned for others with maintaining alertness over long shifts, and whether workload during typical shifts is manageable.

Within the "Observation" cover term, interview participants described their general observations and observations on maintaining alertness with regard to workload. Examples regarding workload general observations include P1 stated, "Data operator always something they can be doing (i.e., trends, old data, is trend still valid). Cycles every 9-10 minutes needed to send next set of commands to robot," and P7 stated, "Sometimes overloaded (when robot was stuck), maybe structure on how to replay what just happened." Examples regarding workload alertness observations include P2 stated, "As the days went on, that was harder for alertness," P3 stated, "Two hours on/off helps with alertness...test conductor verbalized subroutines of what is going on, maintaining constant attention, always something happening, and need to capture it. Verbalize tasks, checking in on the task," P7 stated, "When things were without issues, harder to focus (imagine for nightshift), then switch out with the other primary operators," P8 stated, "Logging things such as notes of what happened, grab timestamps on video, cyclical such as passing over the same rock," and P9 stated, "coffee and desk in standing mode."

Within the "Recommendation" cover term, interview participants described their recommendations on workload. For example, P3 stated, "Some operations had forced checks that forced you to keep eyes and mind on a task which is maybe a lesson to have each test conductor talk through each operation even on routine to keep that focus," P5 stated, "Tempting to think to do day job during operations but should not bring day job into mission control room because needs to fully immersed. When little to monitor, have a list of tasks and questions that the lead wants answered (that might require an analysis, such as a wheel slip. Working on related tasks such as interpreting/analyzing data leads to enhanced engagement," P7 stated, "Maybe provide a structure on how to replay what just happened," and P8 stated, "Lessons learned (on alertness strategies)."

Table 9. Domain 9

Domain 9: IPEx Control Room Operators' Design Considerations on Workload

Domain 9	Cover Term	Included Term	Conjectures
Workload	Observation	General	9.1 Work to perform.
		Alertness	9.2 Verbalized status during shift. 9.3 Logging notes. 9.4 Other (i.e., caffeine, standing, etc.).
	Recommendations	--	9.5 Forced checks. 9.6 Fully immerse in mission control tasks. 9.7 Procedures/Lessons learned.

Domain 10: Domain 10 is "IPEx Control Room Operator's Design Considerations of Rest Area & Breaks" (see Table 10). One cover term was identified, "Recommendations." There was no included term for the "Recommendation" cover term. Domain 10 corresponded to RQs on reset areas and breaks regarding whether operators had adequate time and access to the rest areas during their shift, and any recommendations for changes to make the rest area more effective and comfortable for managing fatigue.

Within the "Recommendation" cover term, interview participants described their recommendations on rest areas and breaks. For example, P1 stated, "Hand weights and portable treadmills," P3 stated, cots/mattresses in quiet dark room away from the main hallway," P5 stated, "Massage chair," P6 stated, "Futons and exercise equipment," and P8 stated, Exercise equipment/balance zone."

Table 10. Domain 10

Domain 10: IPEx Control Room Operators' Design Considerations on Rest Area & Breaks

Domain 10	Cover Term	Included Term	Conjectures
Rest Area & Breaks	Recommendations	--	10.1 Exercise equipment. 10.2 Mattresses in dark room. 10.3 Massage chair.

Domain 11: Domain 11 is "IPEx Control Room Operator's Design Considerations of Food Area" (see Table 11). Two cover terms were identified: "Observation" and "Recommendations." There were no included terms for the cover terms. Domain 11 corresponded to RQs on the food area regarding whether the food preparation/storage area was sufficient for long shifts, and any recommendations for improvement.

Within the "Observation" cover term, interview participants described their observations of the food area. Examples regarding food area observations include P2 stated, "Lots of food was available," P3 stated, "Mental boost to have food – it was nice...distance to food area was fine," P5 stated, "Food is refreshing/energizing."

Within the "Recommendation" cover term, interview participants described their recommendations on the food area. For example, P1 stated, "Griddle and/or outdoor grill," P3 stated, "Expand variety of food, restocking food, what needs to be refreshed not to have spoiled

food, etc.,” P5 stated, “Junk food is not good for you so healthy options are best and to keep informed of team members’ dietary restrictions,” P6 stated, “Healthy food would be great,” P7 stated, “Vending machine in the building. Reliable water dispenser” and P8 stated, “Toaster oven.”

Table 11. Domain 11

Domain 11: IPEX Control Room Operators’ Design Considerations on Food Area

Domain 11	Cover Term	Included Term	Conjectures
Food Area	Observation		11.1 Food availability appreciated. 11.2 Distance to food area was appropriate.
	Recommendations	--	11.3 Toaster oven/Grill/Griddle. 11.4 Food options. 11.5 Process for restocking food/monitoring expired food. 11.6 Vending machine. 11.7 Reliable water dispenser.

5. Conclusion

This analysis highlights opportunities for incremental improvements across the control room's design, processes, and amenities, fostering a more efficient and supportive environment for the IPEX team. The recommendations within the 11 domains consisted of 50 recommendations for improvement of displays, room layout, individual desk layout, lighting, shiftwork, shift changeover, control room employee interaction, control room environment, workload, rest area and breaks, and food area. Some of these recommendations are discussed below:

Display Usability: Menu navigation, zoom/adjustability for control room operators of the IPEX camera views, font size, GUI enhancements (i.e., readability, alerts, monitoring, color usage), and adding details and categorization to camera feeds.

Room Layout: Printer inside control, whiteboard on wheels, longer extension cords, status visual for where the robot is in the cycle, cables reworked, visitors behind glass, minimal adjustments to desks to move farther from walls, and allow additional walking space for team members.

Individual Desk Layout: Increased desk adjustability, desk spacing, and desk accessories (i.e., cup holders, stress balls, adapters, and increased access to balance boards, walking treadmill desks).

Lighting: Experimentation with dim lighting and adjusting other visited facility areas; add individual desk lighting that is brighter for those desiring increased lighting.

Shiftwork: Experimentation with three shifts versus two, length of shifts overlapping at changeover, experimentation with a sleep area, and adding blankets to the rest area.

Shift Changeover: Checklists, increased training on GUIs before missions, briefing for new shifts, increased procedures, and increased system capability to store data to share with new shifts (i.e., video, telemetry, etc.).

Control Room Employee Interaction: Standardize team leader roles in maintaining vigilance of team members and in providing status checks, conduct additional briefings, develop control room norms to formalize culture, and minimize tours to non-critical operations and relocate if the room can be redesigned to a glass view for visitors during operations.

Control Room Environment: Coordinate with safety to determine the feasibility of individual desk heating/cooling desk fans, glass enclosures for visitors (and, potentially, after testing, shift changeover conversations), and wall décor enhancements that serve a functional purpose for the IPEX control room.

Workload: Lessons learned shared among all shifts on alertness strategies during times of low workload (i.e., verbalizing tasks, logging notes, reviewing past trends, forced checks, etc.), and procedures on staying fully immersed in mission-only responsibilities when entering the control room.

Rest Area & Breaks: During shift rotation, when operators are in the rest area for two hours, exercise equipment (i.e., KSC uses the term Balance Zones), sleep areas, or access to a massage chair could assist in invigorating operators prior to reentering the control room.

Food Area: Access to cooking equipment (i.e., toaster oven, griddle, grill), vending machine, reliable water dispenser, process for restocking/monitoring expired food, and increasing food options to include healthy options or options in alignment with the dietary restrictions of operators would be viewed favorably by operators.

The 33 open-ended questions reflect the researchers' goals to explore a more global approach to identifying recommendations for enhancement from the individuals who work directly in IPEX operations. The study limitations include the specific control room operators, because if the study were replicated with different participants, different responses could have provided different levels of detail or content, or the authenticity of their responses. Therefore, the results might be different if the current study were replicated with different control room operators. Thus, the gap in research and the value of this initial study is to provide a baseline for further studies that can create convergent validity for this methodological approach.

Future research would consist of continuing this study methodology within a broader, more diverse population of professionals, from IPEX control operators to air traffic controllers, that could reveal more nuanced, actionable trends. This study's expansion of Spradley's (2016) ethnographic methodologies into new control room operator social science research can also inform future researchers in creating new analytical frameworks for describing cultural phenomena, as this study did by examining the human factors components of control room operators and their shifts. Furthermore, conducting focus groups within different IPEX shifts would be another research area to explore, in addition to expanding to other populations with control room environments, such as the military. This would assist in understanding team dynamics and how different shifts successfully interact. The themes of interaction strengths from one shift would be captured, and lessons learned would be shared with other shifts. Also, usability studies could be conducted within the control room to identify display screens and functionality that would further optimize the human performance and efficiency of IPEX control room operators while maximizing the safety of future missions. There is a need for continuous improvement within operations, especially within safety-critical systems such as those in the space industry.

6. Disclaimer Statements

Funding: None

Conflict of Interest: None

7. References

- Ary, D., Jacobs, L. C., & Sorensen, C. (2010). *Introduction to research in education* (8th ed.). Wadsworth, Cengage Learning.
- Buckles, B. C., Schuler, J. M., Nick, A. J., Smith, J. D., & Muller, T. J. (2022). ISRU pilot excavator – Development of autonomous excavation algorithms. *Space Resources Roundtable, XXII Meeting*.
- Creswell, J. W. (2013). *Qualitative inquiry and research design: Choosing among five approaches* (3rd ed.). SAGE Publications.
- J. M. Cloud et al., "The IPEx Autonomy Test-Site: Terrestrial Testing of Autonomous Excavation in Lunar South Pole Conditions," 2025 IEEE Aerospace Conference, Big Sky, MT, USA, 2025, pp. 1-14, doi: [10.1109/AERO63441.2025.11068688](https://doi.org/10.1109/AERO63441.2025.11068688)
- Gormly, K. B. (2023). How commercial landers are changing lunar exploration. *Air and Space Quarterly, Fall*.
- Heiken, G., Vaniman, D., & French, B. M. (1991). *Lunar sourcebook: A user's guide to the Moon*. Cambridge University Press.
- NASA Office of the Chief Technologist. (2020). *Technology Readiness Assessment Best Practices Guide* (SP-20205003605).
- Mueller, R. P., Smith, J. D., Schuler, J. M., Nick, A. J., Gelino, N. J., Leucht, K. W., Townsend, I. I., & Dokos, A. G. (2016). Design of an excavation robot (RASSOR) 2.0. *ASCE Conference on Engineering Science, Construction, and Operations in Challenging Environments*.
- Sanders, G. B. (2018). Advancing in situ resource utilization capabilities to achieve a new paradigm in space exploration. *AIAA SPACE and Astronautics Forum and Exposition*. <https://doi.org/10.2514/6.2018-5124>
- Schuler, J. M., Smith, J. D., Nick, A. J., Buckles, B. C., Dyas, J. E., Ortega, V. V., Cloud, J. M., Dokos, A. G., Zhang, E. L., Wang, J. J., Baron, M. A., Muller, T. J., Clark, C. J., & Howe, M. W. (2024). ISRU pilot excavator (IPEx) technology readiness level 5 design overview. *AIAA Accelerating Space, Commerce, Exploration, and New Discovery Conference*.
- Sun, V. Z., Hand, K. P., Stack, K. M., Farley, K. A., Milkovich, S., Kronyak, R., et al. (2023). Exploring the Jezero crater floor: Overview of results from the Mars 2020 Perseverance rover's first science campaign. *Journal of Geophysical Research: Planets*, 128(6), e2022JE007613. <https://doi.org/10.1029/2022JE007613>.
- Walker, M. E., Gramopadhye, M., Ikeda, B., Burns, J., & Szafir, D. (2024). The Cyber-Physical Control Room: A mixed reality interface for mobile robot teleoperation and human-robot teaming. *Proceedings of the ACM/IEEE International Conference on Human-Robot Interaction (HRI '24)*. <https://doi.org/10.1145/3610977.3634981>.

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INVESTIGATING THE RELATIONSHIP BETWEEN POPULATION DENSITY SURROUNDING AN AIRPORT AND THE NUMBER OF WILDLIFE STRIKES PER OPERATION

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Abstract

This study investigates the relationship between population density and wildlife strikes per operation at 78 airports in the Southeastern Region of the United States: Florida, Georgia, North Carolina, and South Carolina. The data are derived from the year 2020. The descriptive statistics revealed consistent wildlife strike rates across varying operations and population densities. The inferential statistics revealed a very weak correlation and no statistical significance. After removing the outliers, the correlation and statistical significance remained the same. Despite expectations and support from literature findings, the data revealed no relationship between population density and wildlife strikes per operation, indicating further research is necessary to improve safety.

Keywords: *Wildlife Strikes; Bird Strikes; Airports; Population Density; Southeastern US.*

1. Introduction

The United States has a growing air transport industry, resulting in an increase in interactions between flight operations and wildlife. The Federal Aviation Administration (FAA, 2024a) has documented thousands of wildlife strikes through their National Wildlife Strike Database (NWSD), emphasizing the need for wildlife mitigation strategies to be implemented, which can be made possible through a better understanding of how an airports' surrounding environment can influence wildlife habitats and activity, and ultimately the total risk posed to wildlife strikes in that surrounding area. The purpose of this study was to investigate the relationship between population density surrounding an airport, and the airport's associated number of wildlife strikes per operation in 2020. Population density was measured utilizing population figures reported in the US 2020 Census for individual ZIP codes surrounding an airport, which were then divided by surface area covered by the ZIP codes (United States Census Bureau, 2020). Wildlife strike data were collected from the FAA's (2024a) NWSD, and operations data for individual airports were collected from the FAA's (2024b) Operations Network (OPSNET).

1.1. Research Question and Hypothesis

The study addressed the following research question: what is the relationship between population density surrounding an airport and the reported number of wildlife strikes per operation? An inverse relationship between population density and reported wildlife strikes per operation at

airports was expected. This is due to the significant threats created by urbanization towards wildlife habitats and populations (Isaksson, 2018). Rural environments with lower surrounding population densities are more likely to be home to thriving wildlife populations, which is anticipated to increase the probability of wildlife strikes within the airport environment and its surroundings.

1.2. Significance

The study provided data on the number of wildlife strikes depending on the population density of airports. This study improved the understanding of wildlife strikes at towered airports of different sizes, and whether the population density surrounding these airports may be related to wildlife strike occurrences. Findings from this research study may have broader implications in the aviation industry as models are developed. The information gathered from this can improve safe aircraft operations for all involved in the aviation industry: commercial aircraft, general aviation aircraft, private aircraft, etc. Further research can help implement wildlife strikes risk assessment models for land-use practices, implement legislation to regulate wildlife hazards, and implement increased training awareness (Blackwell et al., 2009).

The results of this study are generalizable to towered airports located in the Southeastern United States, namely Florida, Georgia, South Carolina, and North Carolina. This is because the sample is representative of that population with regard to climate, species of wildlife inhabiting the land surrounding airports, and airport sizes. In addition, the results may be generalizable to airports with similar weather patterns, climates, and regional airport traffic in the near geographic vicinity.

2. Literature Review

Using public data from the US Census Bureau and the FAA, this research investigated the potential relationship between the population density surrounding an airport and that airport's corresponding number of wildlife strikes per operation annually. An analysis of existing literature and research pertaining to relevant topics is vital in developing a better understanding of key elements pertaining to this research, such as the impact of wildlife strikes on aviation, current wildlife strike prevention and mitigation strategies, and the impacts of urbanization on wildlife.

2.1. Impacts of Urbanization on Wildlife

In the pursuit of identifying a potential relationship between an airport's surrounding population density and reported wildlife strike figures, it is vital to better understand the relationship between urbanized environments and their surrounding wildlife populations. Naturally, an area with a rich and extensive wildlife population and concentration is likely to create an increased threat of wildlife strikes to aircraft operating in its vicinity. Given this, understanding the interactions of wildlife species, populations, and habitats with a highly urbanized and populated surrounding environment can provide a better understanding of the inherent risks posed to aircraft operating at airports surrounded by densely populated areas in comparison to rural environments.

These interactions between urbanized environments and their surrounding wildlife populations can be of great interest for land-use planning with regard to airport development and management of their surrounding areas. Most airports classified as major hubs are situated in peripheral locations of city boundaries, as this is beneficial to obstacle clearance for departing and arriving aircraft, and reduced noise pollution to densely populated areas created by airports with many operations (ICAO, 2015). However, there are also many airports located within city boundaries that are home to many flight operations. These airports are commonly located in metropolitan areas and consist predominantly of regional airports with extensive airline operations, or local airports with significant general aviation operations (FAA, 2022). This variance in the environments surrounding airports may create

inconsistencies in wildlife strike probabilities and risks, and further understanding the environment's connection to wildlife strikes can be of great importance for future land-use planning and identifying airports that may be more vulnerable to wildlife strike hazards.

Urbanization refers to a population's shift towards a concentrated area of land, with land-use efforts focusing on the development of residential, commercial, industrial, and transportation infrastructure (Environmental Protection Agency, 2024). Urbanization is a key driver of landscape conversion, creating significant potential for alterations to wildlife patterns and ecological processes (Lewis et al., 2015). As humans develop new structures, transportation networks, and industrial complexes, the surrounding land transitions from natural green habitats to anthropogenic structures and impervious surfaces that impede ecological flourishing (Isaksson, 2018). This creates significant challenges for local wildlife, who are forced to either adapt to this changing environment, or to entirely avoid these new conditions and migrate elsewhere. Haddad et al. (2015) observed that fragmentation of habitats resulted in a degradation of biodiversity, ecological processes, and species richness both in short-term and long-term experiments and across various habitats. The effects of fragmentation resulted in a species population decline to half of the population in an unfragmented landscape with the same composition (Wiegand et al., 2005).

A primary threat to wildlife in an urbanized habitat comes in the form of environmental changes associated with extensive artificial developments. In such densely populated environments, wildlife populations are more exposed to various toxic anthropogenic substances and are at a highly increased risk for parasite and disease transmission due to the urbanization's interference with ecological processes necessary for wildlife species to flourish (Murray et al., 2019). Birds make up a large portion of species affected by urbanization. Factors, such as increased chemical pollution, increased light and noise pollution, and increased traffic, all contribute towards altered behavior of birds, and risks to survival and reproduction (Seress & Liker, 2015). Many species struggle significantly with survival in habitats experiencing an increasingly dense human population and emigrate due to the challenges faced; these species are known as "urban avoiders" (Isaksson, 2018). However, certain species have also been found to thrive in densely populated areas, with species, such as raccoons, skunks, and red foxes, reaching their highest densities in urban environments (Riley et al., 2003). However, the overall impacts of urbanization on wildlife populations have been found to be predominantly harmful, largely due to habitat fragmentation serving as a key driver in diminished wildlife populations, even if a species could potentially survive and persist through the environmental changes. Fragmentations of natural landscapes in urbanizing environments can alter ecological processes through removal and isolation of native vegetation, which may be crucial for the survival of local species. These alterations and interferences with natural processes ultimately result in smaller wildlife populations, which are now exposed to new threats (Marzluff & Ewing, 2001). These threats can come in the form of increased competition with neighboring species, exposure to larger populations of predators, and increased disturbances and mortality rates from direct human interference (Marzluff & Ewing, 2001).

2.2. Impacts of Wildlife Strikes on Aviation

The first bird strike occurred in 1905 with the Wright Flyer III, almost 100 years ago (Metz, 2020), and bird strikes have long been a safety concern to all involved in the aviation industry since. The financial burdens and safety concerns surrounding bird strikes have resulted in the implementation of safety mitigation strategies in airport planning. Bird strikes are unavoidable as nature and machines are interacting in various airspaces. In the 1960's, wildlife strikes became more frequent due to the increased speed and quietness of aircraft (Dolbeer, 2013). According to Alharbi et al. (2024), the number of wildlife strikes reported between 2013 and 2022 was 145, 007. As technology and the popularity of the aviation industry increases, airlines need to understand how to operate with wildlife in shared airspace.

Financial burdens among the owners and operators of aircraft and airports involved in bird strikes are unavoidable and drastic. In recent reports, it was found that roughly 39 bird strikes were reported daily within the aviation industry (Ferra et al., 2021). Additionally, civil aviation reported roughly 2.83 to 8.19 bird strikes per 10,000 aircraft movements (Metz, 2020). Besides repairing aircraft after bird strikes, the operator must pay for the downtime operations, such as hangar space, and loss of revenue (Ferra et al., 2021). Loss of revenue includes passenger rebooking, aircraft rescheduling and rentals if applicable, and flight cancellations (Metz, 2020). According to FAA NWSD reports by Dolbeer et al. (2015), the average aircraft downtime was around 119.4 hours, repair costs were \$169,349 per incident, and revenue lost from canceled flights were \$28,596. The annual costs related to commercial aircraft repairs due to bird strikes were estimated to be around \$682 million in 2012 (Pitlik et al., 2012) and estimated at least one billion dollars now. No matter the size of the bird strike incident, aircraft downtime has a major effect on the operation of a business, airport, and flight crews. Airport operations can be temporarily impaired due to the removal of wildlife and runway closures that may exist. Aircraft must be inspected no matter the magnitude of the bird strike prior to the next departure to ensure aircraft airworthiness holds its integrity and to ensure safe operations can be maintained (Metz, 2020). With the increased costs of operations, repairs, and accommodations increasing, the implementation of Wildlife Management Plans at airports has been suggested when multiple wildlife strikes have occurred (Wildlife Hazard Management, 2020). They were used to increase communication and collaboration among different airports with similar wildlife presence (Pitlik et al., 2012). The plans entail identifying the types of species around specific airports and determining the correct tools to deter the species away from the airports (Ferra et al., 2021). In 2013, similar plans for decreasing wildlife strike frequency were suggested by Dolbeer and continued to be in 2021 by Ferra et al. This highlights the importance of wildlife strikes being investigated for future research. Suggestions on wildlife management plans from previous research highlight the need for continuous investigation on mitigation strategies.

Safety concerns during bird strikes are relevant to the flight crew and passengers as the potential for sudden deaths among all involved is a possibility. A long history of bird strikes has occurred leading to devastating and remarkable results (Ferra et al., 2021). Wildlife strikes create aerodynamic issues for the aircraft due to the smoothness of the aircraft wing being dented, fractured, or structurally damaged. When this occurs, the aircraft no longer operates normally and requires more input controls by the pilot to maintain a safe attitude, altitude, and airspeed (FAA, 2016). The effects of wildlife strikes highlight how frightening it can be to the flight crews, whose lives are in jeopardy. In reports from 2019, the aviation industry experienced 618 hull losses and 534 fatalities (Metz, 2020). The large number of fatalities can be related to the relationship between aircraft characteristics and the likelihood of bird strikes in critical aircraft parts. Bird strikes are likely to occur and have been reported more frequently to strike at the nose, wings' leading edges, and the engines (Metz, 2020). Engine failures are the most critical of the above parts because they affect performance, handling, and other systems. All of these factors are influential in the detrimental occurrence of fatalities and accidents. Damage tolerances based on the FAA are the following: windshields can withstand 2-pound birds at cruise speed without penetration, structures can withstand 4-pound birds when the velocity is relatively equal to the birds' flight path, and the empennage can withstand 8-pound birds at cruise speed (Metz, 2020). Wildlife strike hazards occur in all sizes. The need to investigate wildlife strikes based on population density surrounding airports is necessary to relieve financial burdens and decrease safety concerns.

2.3. Current Wildlife Strike Prevention and Mitigation Strategies

Wildlife strikes have become a serious hazard to the aviation industry, with a potential to cause serious aircraft damage to a catastrophic accident. Historically, several mitigation strategies have been applied to reduce wildlife strikes and increase overall safety at and around the airports. However, according to Ning and Chen (2024), the underreporting of wildlife strikes remains a major concern. Ning and Chen (2014) stated that there has been previous research using radar around airports attempting to lower the frequency of wildlife strikes via probability estimation (a technique used to determine the likelihood that a bird will fly over a certain runway, broken into three factors: distance, angle, and bird species. The severity estimation is done by questioning experts in the field, and then the results are put into a matrix to refine the answers down to get the most common answer. Probability and severity estimation techniques helped the aviation community to understand the real-time trend in the wildlife strike data rather than relying on historical data, leading to the improvement in prediction of flocks over a specific runway (Ning & Chen, 2014). However, failure of radar systems could potentially lead to an inaccurate estimation of bird reports (Ning & Chen, 2014).

Szafranski et al. (2022) analyzed methods for real-time monitoring and predicting wildlife strike risks. The article discussed military operations and civilian operations that are affected. Szafranski et al. (2022) used formulas and models to predict future trends for where and when operations could be affected, similar to Ning and Chen (2014). Szafranski et al. (2022) research efforts were more directed at military operations globally rather than civilian operations. Algorithms were used for detecting the density of bird flocks and what their speed and direction are (Szafranski et. al, 2022). The algorithm was used in a heavy migration area in Poland with lots of bird activity to test how it could further the understanding of the field (Szafranski et. al, 2022). Most of the studies that have been done are focused on bird populations and how dense populations of birds can be mitigated, so there are fewer accidents. Prior research can be used to relate population density surrounding airports with wildlife strikes, which has not been focused on nearly as much. If mitigation and prevention of wildlife strikes can be improved, then there will be a much safer environment for aviation as a whole, and the more that risk is reduced, the less money will be lost (Szafranski et. al, 2022).

Alhumaidi et al. (2023) discussed the phases of flight that are more likely to have wildlife strikes occur. The data were collected by looking at annual wildlife strike reports and sorting the strikes by which phase of flight they happened during. It was found that the most common phase of flight to have a wildlife strike was during approach, and the least common was when the aircraft was parked (Alhumaidi et al., 2023). Wildlife strikes have become more common over time, impacting the amount of money that the aviation industry has to spend on repairs and mitigation (Alhumaidi et al., 2023). This study showed that the most common time for a wildlife strike is during approach, which means that the aircraft is close to the airport.

It is evident that wildlife strikes are of great importance to the air travel industry in the United States, considering the high potential for considerable costs to safety and financial repercussions. While there are currently wildlife strike risk mitigation efforts in place, there is a lack of research on the potential relationship between land-use surrounding an airport and wildlife strike rates. By investigating this, a new perspective may be considered for future wildlife strike mitigation strategies, and urban development planning in areas directly surrounding an airport.

3. Methods

A correlational study was conducted. The number of wildlife strikes per operation at an airport was correlated with the airport's surrounding population density. Wildlife strike data were collected from the FAA's (2024a) NWSD for the year 2020 using selected towered airports located in Florida, Georgia,

South Carolina, and North Carolina, while the FAA (2024b) OPSNET provided data on the number of annual flight operations in 2020 at the selected airports. After the data were downloaded, the combined population density of the surrounding zip codes was grouped by individual airports. After doing so, the data were organized based on the selected towered airports located in Florida, Georgia, North Carolina, and South Carolina. The counting was conducted using Excel with the Pivot Table function. Reports containing missing data for the selected variables were excluded from the dataset.

Data for the independent variable, population density around selected towered airports, was collected from the United States Census Bureau (2020) Population Census. The data collected from the census consisted of population per zip code and the area of all surrounding zip codes. The populations for all the relevant zip codes were summed and divided by the combined surface areas of the zip codes to provide a figure for the general surrounding population density. All zip codes located within a 5-mile radius from the airport were included. Once data for both the number of wildlife strikes per operation and the population density surrounding each individual airport were collected, it was combined into a spreadsheet for the data analysis.

The data analysis consisted of a set of descriptive statistics (mean, median, range, and standard deviation) on population density, total wildlife strikes, total wildlife strikes per operation, and wildlife strikes per operation for each selected airport. The final dataset was analyzed using RStudio Version 4.4.1, a digital statistics software. Statistical inferences were made using Pearson's r to provide a numerical value for the correlational study. The correlation coefficient indicates a positive or negative relationship between continuous numerical variables, in addition to the strength of the correlation between the two variables.

4. Results

Population data for the research was organized into four sheets containing zip codes that fall within a 5-mile radius of each airport, population and surface area of each zip code, and the cumulative population per square mile of all zip codes surrounding each airport. In Excel, population density was calculated by dividing the cumulative population by the cumulative surface areas of all zip codes within a 5-mile radius of each airport. Wildlife strikes per operation were calculated as the total number of operations for each airport divided by the number of reported wildlife strikes. The final dataset included all wildlife strike reports for 2020 from 78 airports within the states of Florida, Georgia, South Carolina, and North Carolina. Airports with missing operations data from the FAA's (2024b) OPSNET were excluded. Descriptive statistics for total wildlife strikes, wildlife strikes per operation, operations per airport, and population density are shown in Table 1.

A mode of 0 for Wildlife Strike Count and Operations per airport was a consequence of missing data from the databases utilized. Airports with missing data for these variables were excluded from the dataset utilized for descriptive and inferential statistics. The calculated wildlife strikes per operation demonstrated a tendency to remain consistent despite large differences in operations figures and population densities for different airports.

Table 1. Descriptive Statistics for Wildlife Strikes, Operations, and Population Density in 2020

	Mean	Median	Range	SD
Wildlife Strikes Per Operation	0.00016	0.0001	0 - 0.001	0.00018
Wildlife Strike Count	18.39	8	0 - 194	29.45
Operations Per Airport	96,772	87,265	0 - 548,016	80,606.02
Population Density	1,715.62	992.54	50.48 - 7,614.19	1,742.58

A Pearson's r of -0.14 was calculated between population density and wildlife strikes per operation, highlighting a very weak negative correlation between population density and wildlife strikes per operation. The associated p -value of $.23$ highlights that the correlation between the variables is not statistically significant. A scatter plot of the relationship between the two variables can be seen in Figure 1. The assumption of no outliers for the Pearson's r test was not met, so the outliers were removed from the set, and a second test was run. The second Pearson's r showed not much change in the results; there was still a very weak negative correlation with no statistical significance.

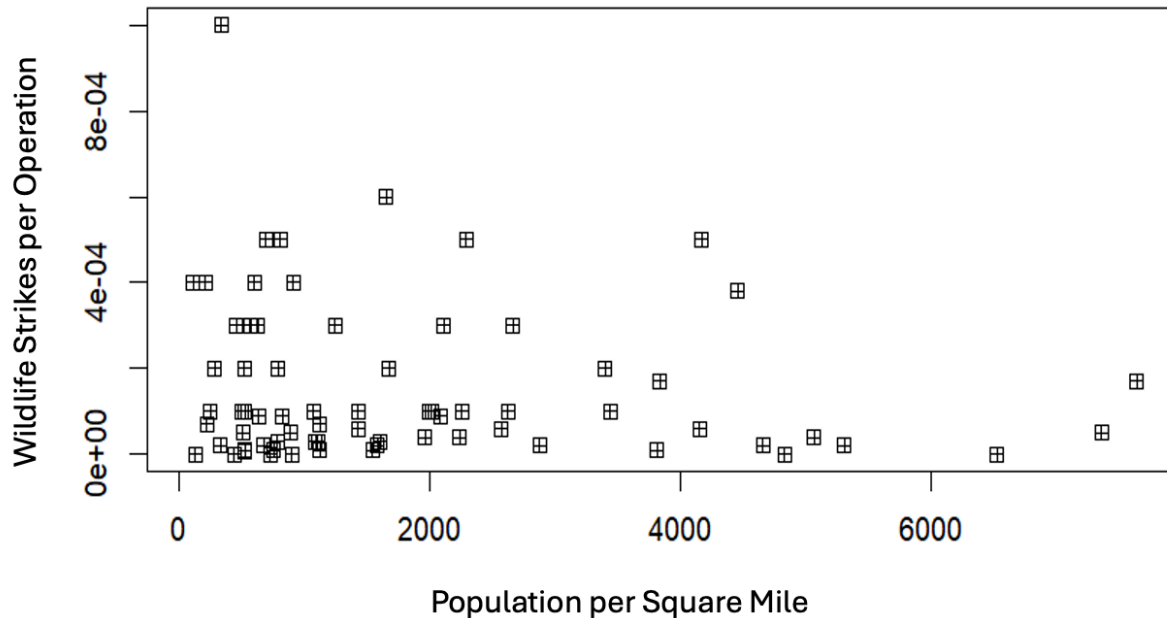


Figure 1. Wildlife Strikes Per Operation Vs. Population Per Square Mile

5. Discussion

The results indicated that the hypothesis, which predicted an inverse relationship between population density and reported wildlife strikes per operation, was not supported. Through an analysis of the dataset utilizing both descriptive and inferential statistics, a very weak negative correlation was identified between the two variables ($r = -0.14$, $p = .23$). The scatterplot portraying the data (Figure 1) further supports this lack of correlation. The second test with no outliers indicated that there was a very weak negative correlation with a Pearson's r value of -0.098 and a p -value of $.43$, showing no statistical significance.

This result contrasts with the expectations created by various findings from the literature review. Lewis et al. (2015) stated that the landscape conversion and fragmentation of habitats creates significant potential for alterations to wildlife patterns and ecological processes. Wiegand et al. (2005) supported this by identifying that fragmentation can result in a species population decline to half of the population in an unfragmented landscape with the same composition. Isaksson (2018) attributed this to “urban avoiders”, referring to the various species that struggle to cope in highly urbanized environments consistent with densely populated areas, and are forced to migrate elsewhere. The extensive research outlining the harmful effects of urbanization on wildlife populations led to the expectation that a damaged ecosystem and decline in wildlife populations would result in a lower threat of wildlife to aircraft operations in the vicinity, and a consequent decrease in reported wildlife

strikes. However, Isaksson's research also noted the existence of species that thrive in urbanized environments, which may provide an explanation for the findings in this study

A limitation to this study can be seen in the data utilized. While the databases originate from reputable government agencies, the FAA's (2024a) NWSD relies on voluntary reports of wildlife strikes made by pilots to gather data. For this reason, the figures may not entirely represent the actual number of wildlife strikes at each airport due to the possibility of unreported events. However, it is assumed that the figures are at least proportional to the number of wildlife strike occurrences. Additionally, the most recent US Census was conducted for the calendar year of 2020. This data was selected as it is collected by a government entity, providing the most accurate figures and allowing the different data sources to be used together. Given that it is currently 2024, there is a high likelihood of changing populations, meaning that results may no longer apply. However, this change is assumed to be negligible.

Despite the lack of correlation between population density surrounding an airport and the rate of wildlife strikes per operation, given the evident effects of urbanization on wildlife populations identified in the literature review, there is still potential for further research on the interaction between urbanization and aircraft wildlife strike occurrences. Future research can take a historical approach, utilizing a smaller airport sample size and focusing on reported wildlife strikes at airports over the previous decade in comparison to the changing population per year around each airport. Additionally, a correlational study could consider the airports with the highest reported annual wildlife strikes in the United States to evaluate a potential pattern with the surrounding population density of those airports. Other confounding variables, such as wildlife strike mitigation strategies at each airport, local climates, and local species populations, may also be considered to allow for a more accurate and representative analysis. With the current findings, no major suggestions can be made to assist with reducing the threat posed to aviation by wildlife strikes; however, further research in this field can be of great help with future airport developments and land-use planning to assist in doing so.

6. Disclaimer Statements

Funding: None

Conflict of Interest: None

7. References

- Alharbi, M. M. O., Meechan, C., Sharma, V., & Weeler, B. E. (2024). Annual wildlife strike rate by damage category in the United States 2013-2022. *Industry, Engineering & Conference Management Systems Conference*. <https://doi.org/10.62704/10057/28723>
- Alhumaidi, S. H., Alruwaili, I. Y., & Wheeler, B. (2023). U.S. wildlife strikes by phase of Flight. *Journal of Management and Engineering Integration*, 16(1), 39–47. <https://doi.org/10.62704/10057/25980>
- Dolbeer, Richard A., (2013) "The History of Wildlife Strikes and Management at Airports". *USDA National Wildlife Research Center - Staff Publications*. 1459. http://digitalcommons.unl.edu/icwdm_usdanwrc/1459
- Environmental Protection Agency. (2024). *Urbanization Overview*. <https://www.epa.gov/caddis/urbanization-overview>
- FAA. (2016). Pilot's handbook of aeronautical knowledge. United States Department of Transportation. FAA-H8083-25B. [faa.gov/sites/faa.gov/files/pilots/pilot_handbook.pdf](https://www.faa.gov/sites/faa.gov/files/pilots/pilot_handbook.pdf)
- Federal Aviation Administration. (2022). Airport Categories. US Department of Transportation https://www.faa.gov/airports/planning_capacity/categories
- Federal Aviation Administration. (2024a). *National Wildlife Strike Database*. US Department of Transportation. <https://wildlife.faa.gov/home>

- Federal Aviation Administration (2024b) *The Operations Network (OPSNET)*. US Department of Transportation. <https://aspm.faa.gov/opsnet/sys/main.asp>
- Ferra, G., Alghamdi, H., Wheeler, B. E., & Li, T. (2021). Comparing the Frequency of Reported Wildlife Strikes by Region in the United States. *Journal of Management & Engineering Integration*, 14(1), 37-45. <https://doi.org/10.62704/10057/24767>
- Haddad, N. M., Brudvig, L. A., Clobert, J., Davies, K. F., Gonzalez, A., Holt, R. D., Lovejoy, T. E., Sexton, J. O., Austin, M. P., Collins, C. D., Cook, W. M., Damschen, E. I., Ewers, R. M., Foster, B. L., Jenkins, C. N., King, A. J., Laurance, W. F., Levey, D. J., Margules, C. R., ... Townshend, J. R. (2015). Habitat fragmentation and its lasting impact on Earth's ecosystems. *Science Advances*, 1(2). <https://doi.org/10.1126/sciadv.1500052>
- ICAO. (2015). *Synergy Between Airports and Urban Development For Sustainable Development* <https://www.icao.int/ESAF/Documents/meetings/2016/UN-Habitat-ICAO%20Experts%20Meeting%202016/Documents/Concept%20Note%20Compressed%20-%2004%20August%202016%20publishing%20version.pdf>
- Isaksson, C. (2018). Impact of urbanization on birds. In: Tietze, D. (eds) *Bird Species. Fascinating Life Sciences*. Springer, Cham. https://doi.org/10.1007/978-3-319-91689-7_13
- Lewis, J. S., Logan, K. A., Alldredge, M. W., Bailey, L. L., VandeWoude, S., & Crooks, K. R. (2015). The effects of urbanization on population density, occupancy, and detection probability of Wild Felids. *Ecological Applications*, 25(7), 1880–1895. <https://doi.org/10.1890/14-1664.1>
- Marzluff, J. M., & Ewing, K. (2001). Restoration of fragmented landscapes for the conservation of birds: A general framework and specific recommendations for urbanizing landscapes. *Restoration Ecology*, 9(3), 280–292. <https://doi.org/10.1046/j.1526-100x.2001.009003280.x>
- Metz, I. C., Ellerbroek, J., Mühlhausen, T., Kügler, D., & Hoekstra, J. M. (2020). The bird strike challenge. *Aerospace*, 7(3), 26. <https://doi.org/10.3390/aerospace7030026>
- Murray, M. H., Sánchez, C. A., Becker, D. J., Byers, K. A., Worsley-Tonks, K. E., & Craft, M. E. (2019). City Sicker? A meta-analysis of Wildlife Health and Urbanization. *Frontiers in Ecology and the Environment*, 17(10), 575–583. <https://doi.org/10.1002/fee.2126>
- Ning, H., & Chen, W. (2014). Bird strike risk evaluation at airports. *Aircraft Engineering and Aerospace Technology*, 86(2), 129-137. <https://doi.org/10.1108/AEAT-07-2012-0111>
- Pitlik, T. J., & Washburn, B. E. (2012). Using bird strike information to direct effective management actions within airport environments. In *Proceedings of the Vertebrate Pest Conference* (Vol. 25, No. 25). <https://doi.org/10.5070/V425110493>
- Riley, S. P., Sauvajot, R. M., Fuller, T. K., York, E. C., Kamradt, D. A., Bromley, C., & Wayne, R. K. (2003). Effects of urbanization and habitat fragmentation on Bobcats and coyotes in Southern California. *Conservation Biology*, 17(2), 566–576. <https://doi.org/10.1046/j.1523-1739.2003.01458.x>
- Seress, G., & Liker, A. (2015). Habitat urbanization and its effects on birds. *Acta Zoologica Academiae Scientiarum Hungaricae*, 61(4), 373–408. <https://doi.org/10.17109/azh.61.4.373.2015>
- Szafrański, B., Zieja, M., & Wójcik, J. (2022). The review of methods for a real-time monitoring and forecasting bird strike risk level. *Journal of Physics: Conference Series*, 2198(1), 012002. <https://doi.org/10.1088/1742-6596/2198/1/012002>
- US Census Bureau (2022). *2020 Census*. Census.gov. <https://www.census.gov/programs-surveys/decennial-census/decade/2020/2020-census-main.html>
- Wiegand, T., Revilla, E., & Moloney, K. A. (2005). Effects of habitat loss and fragmentation on population dynamics. *Conservation Biology*, 19(1), 108–121. <https://doi.org/10.1111/j.1523-1739.2005.00208.x>
- Wildlife Hazard Management, 14 C.F.R. § 139.337 (2020) [eCFR :: 14 CFR 139.337 -- Wildlife hazard management. \(FAR 139.337\)](https://www.ecfr.gov/current/title-14/chapter-I/subchapter-B/part-139/subpart-1/section-139.337)

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A COMPREHENSIVE WORKFLOW FOR 3D RECONSTRUCTION OF THE FEMALE KNEE FROM CT DATA

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Abstract

This study focuses on modeling the bone anatomy of the female knee using Computed Tomography (CT) scan data and advanced software tools Materialize Mimics and Geomagic Wrap. By processing radiological images from the Visible Human Project dataset, a comprehensive workflow was established to create detailed 3D models of the patella, femur, tibia, and fibula. Key steps included extracting image slices, creating masks to isolate individual bones, and utilizing precise cleaning and surfacing techniques to refine geometry. Challenges included handling complex bone shapes and ensuring model accuracy for finite element analysis. The process underscores the utility of integrating software tools for medical modeling and lays a foundation for future advancements in personalized healthcare. Additionally, an attempt is made to model the cancellous bone in each of the mentioned bones.

Keywords: *Biomechanics; Knee; Computed Tomography; Mimics; Geomagic Wrap; CAD.*

1. Introduction

The knee is one of the body's most important joints, providing a large range of motion while withstanding substantial stress and strain. Understanding how these loads act on knee structures informs both prosthetic design and clinical repair strategies. One effective approach is to convert computed-tomography (CT) images into a computer-aided design (CAD) model and then perform finite-element analysis (FEA) on that model. For this study we used the publicly available Visible Human Project CT data sets—released by the Lister Hill National Center for Biomedical Communications and hosted by the National Library of Medicine—to build a CAD model of the female knee, focusing on the distal femur, proximal tibia and fibula, and the patella (National Library of Medicine, 2021; Ackerman, 1998).

2. Literature Review

Patient-specific anatomical modeling and finite-element analysis (FEA) have become central to modern orthopedic implant design. Conventional total knee arthroplasty (TKA) leaves approximately 20% of recipients dissatisfied, largely because generic components mismatch patient anatomy (Mercader et al., 2021). Ramavath et al. (2023) add that standard manufacturing is slow, costly, and prone to anatomical errors—an argument for personalized solutions.

The personalized workflow begins with high-resolution CT data. Advanced segmentation platforms such as Materialise Mimics (Materialise NV, 2024) and Geomagic Wrap (3D Systems, 2024) convert these images into detailed three-dimensional surface models, providing the geometry required for reliable FEA (Pitocchi et al., 2020; Vasiliadis et al., 2024). Accurate anatomical modeling is crucial for generating reliable finite element simulations, as demonstrated in previous studies

modeling prosthetic socket pressure distributions and limb interfaces (Surapureddy et al., 2016; Richardson et al., 2012).

Harrysson, Hosni, et al. (2007) demonstrated that CT-derived, patient-specific femoral components reduce stress concentrations that can trigger loosening. More recent knee-specific modeling by Mercader et al. (2021) emphasized the importance of capturing individual knee geometry and kinematics, which is crucial for enhancing surgical planning and assessing biomechanical alterations following surgery. Zanjani-Pour et al. (2020) reinforced these findings, demonstrating that detailed modeling of cartilage layers and menisci significantly improves the accuracy of biomechanical predictions within knee joint simulations.

Validated digital models feed directly into additive manufacturing processes. Harrysson, Cansizoglu, et al. (2007) discussed advancements such as electron beam melting, enabling the production of highly specific implants tailored to patient anatomy. Sharma and Soni (2021) further demonstrated how direct metal laser sintering (DMLS) can rapidly fabricate metal implants from detailed CAD models, underscoring the importance of accurate CAD data preparation. Fused deposition modeling (FDM) also offers a rapid approach to producing polymer trial components (Ramavath et al., 2023). Mahmoud and Elbestawi (2017) elaborated on additive manufacturing's ability to leverage patient-specific data to achieve complex, tailored mechanical properties, broadening the potential for customized implant applications.

Finally, 3D-printed anatomical guides and biomimetic implant geometries enhance surgical planning and promote osseointegration (Meglioli et al., 2020; Kladovasilakis et al., 2020). Together, these advances integrate imaging, simulation, and manufacturing into a seamless pipeline that increases surgical precision and improves functional outcomes for knee-replacement patients.

3. Methodology

3.1. Acquisition of Computed Tomography Data

The first step in creating the models was to obtain the necessary CT images. These images were accessed from the National Institutes of Health Visible Human Project female dataset (National Library of Medicine, 2021). The dataset contains 1,734 images, each separated by approximately one millimeter. The images are ordered from top to bottom, with the first image (labeled 1001) corresponding to the top of the head and the final image (2734) corresponding to the bottom of the feet.

Downloading the entire set would have been time-consuming and would have required substantial disk space. To estimate which images were needed, prior research on average knee height was consulted (Teichtahl et al., 2012), indicating that the knee is typically located at approximately 30.5% of body height. To ensure complete capture of the knee region, images spanning from 25% to 35% of body height were initially selected, corresponding to slices 2,125 to 2,300.

The image files were initially downloaded as compressed *.fre.Z files. A free program, 7-Zip, was used to decompress these into *.fre files, which could then be imported into Materialise Mimics.

3.2. Segmentation

The process of segmenting the bones was performed using Materialise Mimics. The CT slices consist of voxels, each representing a density value of the scanned anatomy, measured in Hounsfield units (HU). To separate the bones of interest from surrounding tissues, an upper and lower HU threshold was specified. The default threshold values for cortical bone were initially applied, with a

lower limit of 226 HU and an upper limit of 1768 HU.

The Split Mask tool was used to generate individual masks for each bone of interest, including the right and left patella, femur, fibula, and tibia. A mask represents a selection of voxels within the medical image that share specific characteristics, such as intensity values, allowing for isolation of anatomical structures. The Split Mask command is highly automated, enabling the user to separate bones by selecting a few representative voxels from each structure, after which the software automatically generated the corresponding 3D geometry. Similar workflows for converting medical imaging into CAD models have been previously employed in plantar fasciitis studies, where CT data of the foot was segmented and modeled for finite element applications (Knapp, et al., 2016).

A total of eight masks were created, and their appearance across different anatomical views is illustrated in Figure 1.

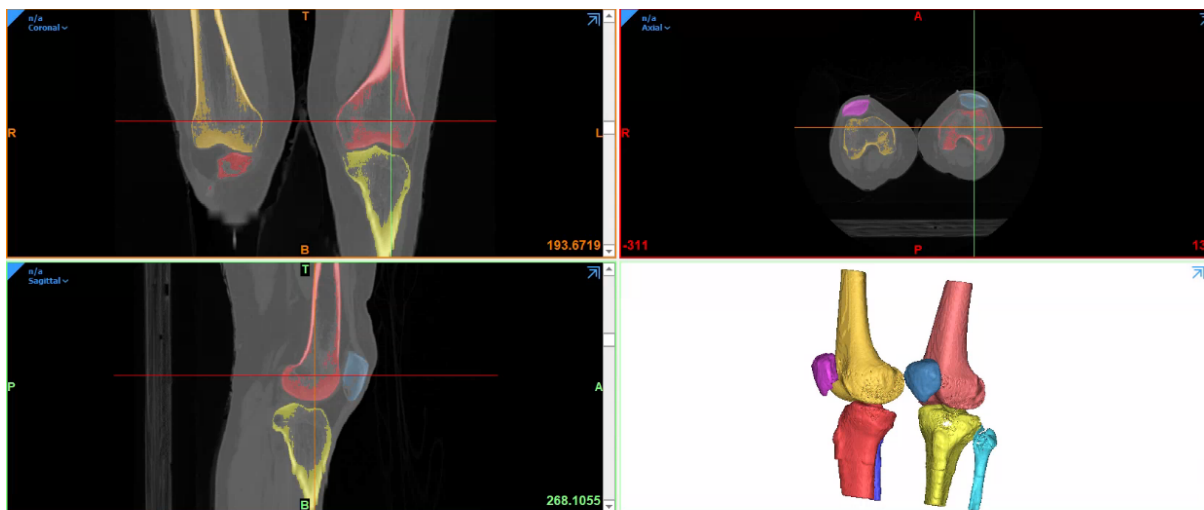


Figure 1. Masks Created in Mimics

The masks for the right knee were further refined to improve accuracy. Because the initial thresholding values were based on estimated cortical bone density, they did not perfectly match the data, as evidenced by numerous holes in the geometry. To address this, the thresholding parameters were adjusted. An optimal lower threshold of 140 HU was established, which better captured missing bone geometry while minimizing the presence of unwanted spikes.

Following threshold adjustment, the Edit Mask tool was used on individual axial slices to manually add or erase geometry as needed. Once refinement was complete, parts were created from the patella, femur, fibula, and tibia masks and saved as STL files, enabling export into Geomagic Wrap for further processing and surface refinement.

3.3. Model Refinement

3.1.1. Model Cleaning

While some initial editing and cleaning were performed in Mimics, the majority of the modeling process was conducted in Geomagic Wrap. The workflow for each bone followed a consistent procedure, divided into two main stages: (1) cleaning, primarily performed under the "Polygons" application, and (2) surfacing, performed under the "Exact Surfaces"

application.

The cleaning process began with remeshing the models using the Remesh command from the Repair toolset, with the "Use Existing Boundaries Only" option selected and "Keep Boundaries" toggled off. Following remeshing, the Mesh Doctor command was applied with Auto-Repair mode enabled to address issues such as open edges, intersections, spikes, tunnels, and holes. The Remove Spikes operation was also performed at a 50% smoothness setting to further eliminate sharp features.

To refine the external surfaces of the bones, the Defeature Repair command was used to remove prominent bumps and visible surface depressions. Manual smoothing was then completed using the Sandpaper tool to address any remaining irregularities. Geometry for these operations was selectively targeted using the Lasso selection tool.

3.1.2. Removal of Interior Geometry

To develop accurate external surface models of each bone, the interior geometry was completely cleaned out. During the segmentation process in Mimics, the thresholding focused on cortical bone, which resulted in unfilled internal regions. When the STL files were generated, the interiors contained numerous small, disconnected surfaces, referred to as "noise surfaces," which could interfere with subsequent finite element analysis and therefore needed to be removed.

An example of cleaned interior geometry is shown in Figure 2, which uses a clipping plane through the patella; the yellow coloring highlights the interior surface, while the blue is for the outside surface.

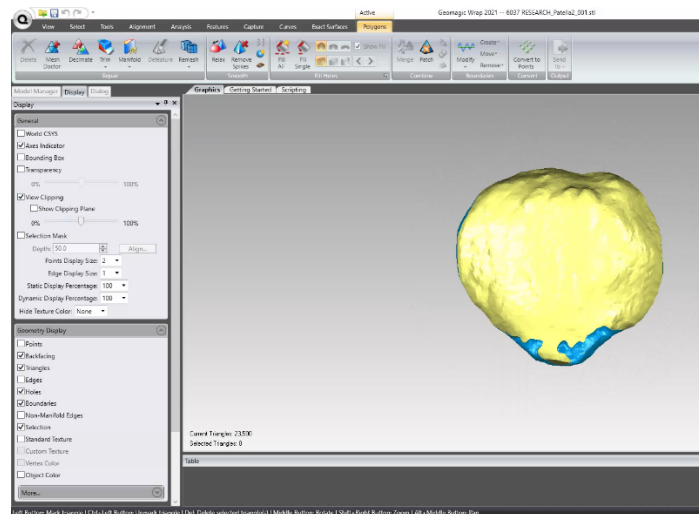


Figure 2. Clipping Plane View of Patella

To edit the internal geometry, the Clipping command—accessed under the Display panel—was utilized by selecting the View Clipping Box option. This created a plane based on the current viewing angle, and the depth of the clipping plane could be adjusted with a slider to progressively expose the interior. For the patella, shown in Figure 2, there was no significant internal geometry to remove due to careful thresholding and manual corrections during the mask generation stage. However, for the other bones, internal surfaces remained and needed

to be manually selected and deleted by viewing the models at different angles. Figure 3 shows the femur using a clipping plane, where the external surface appears blue and the internal surface appears yellow. In this view, internal surfaces that required removal are clearly visible.

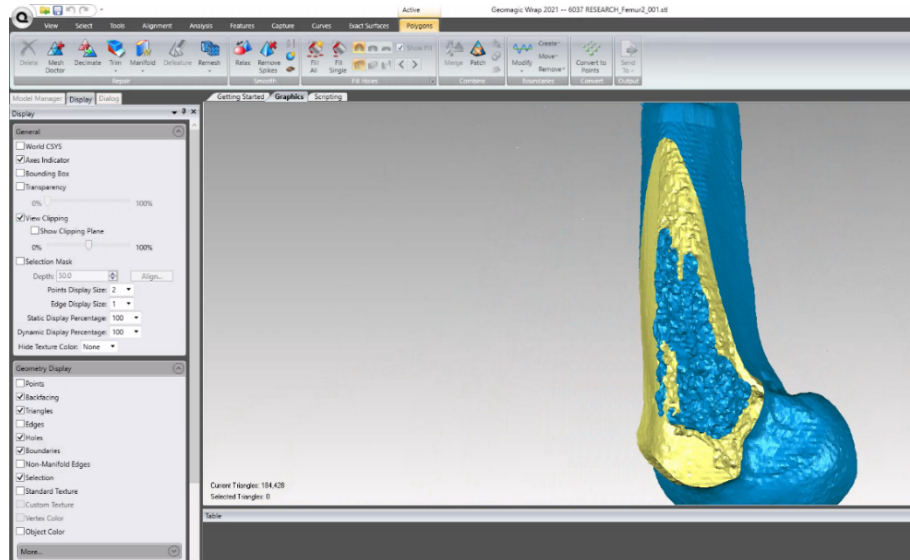


Figure 3. Clipping Plane View of Femur

Once all interior geometries were removed, any holes created during polygon deletion were repaired using various Fill Holes commands. In addition, the proximal ends of the femur and tibia were capped with flat surfaces using Fill Holes to ensure the external surfaces could later be fully wrapped. Figure 4 provides a view into the tibia interior, highlighting the bottom hole that was subsequently filled.

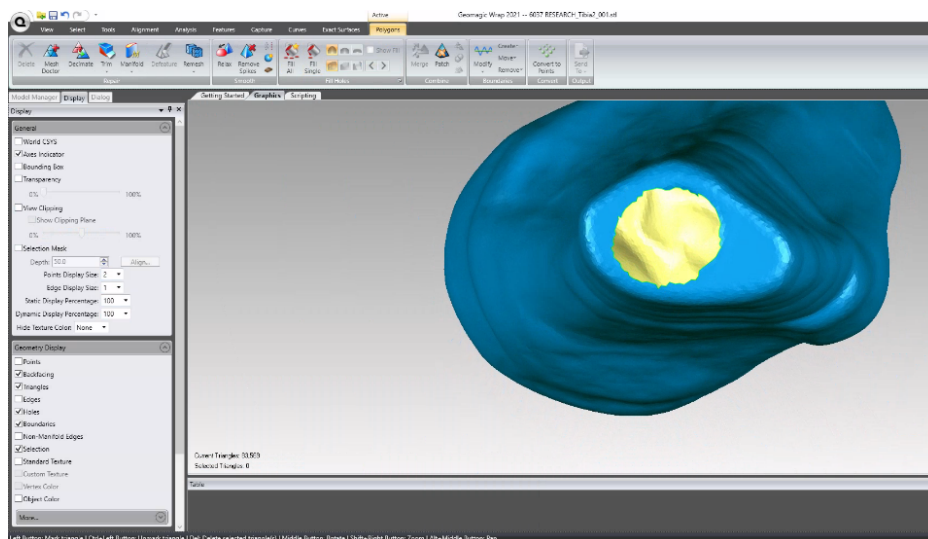


Figure 4. Distal View of the Proximal Tibia Model, Illustrating the Hollow Internal Geometry

After removal of the internal surfaces and closure of all holes, the Remove Spikes command was applied at 100% intensity, followed by Relax and Quick Smooth operations. These steps ensured a smooth, continuous outer surface, critical for generating high-quality models suitable for finite element analysis.

3.1.3. Development of NURBS

NURBS (Non-Uniform Rational B-Splines) surfaces are a mathematical representation of 3D geometry that provide smooth, precise, and editable models. They are essential for converting scanned 3D data into CAD-compatible formats, enabling accurate modifications and reliable finite element modeling and analysis. Since raw scan data consists of polygonal meshes, such as STL files or point clouds, NURBS surfaces are generated to create continuous and structured models. The process begins by extracting surface features from the polygon mesh and then applying NURBS surfaces either through automated or manual methods.

To initiate the surfacing process, the Exact Surfacing command was used. The AutoSurface tool would initially generate a proposed contour, patch, and grid layout, which was reviewed to assess its quality. For the patella, the automatically generated contour layout was ideal and retained. However, for the other bones, the automatically created surfaces, grids, patches, and contours were removed in favor of manually controlling the NURBS patch layout to achieve greater accuracy.

Defining the contours—boundaries of the patches—was a critical step in model creation. Contours needed to reflect the natural geometry of the bone while also facilitating the application of loads and constraints for finite element analysis. Moreover, it was essential that patches met cleanly at their boundaries. Because contour layout determined the patch structure, the femur and tibia contours had to be adjusted and recreated multiple times to meet these requirements.

After finalizing the contour layout, the Subdivide operation was used to create additional points for better surface control. The Construct Patches command was then applied to generate an initial patch network. From there, the Shuffle command, located in the Patches tool group, was used to reorganize the panels into an orderly arrangement. The goal was to align all patches into a grid-like layout within each contour, with patches as close to square as possible, forming a rectangular pattern across the surface. Examples of the resulting patch layouts for the patella and femur are shown in Figures 5 and 6, respectively.

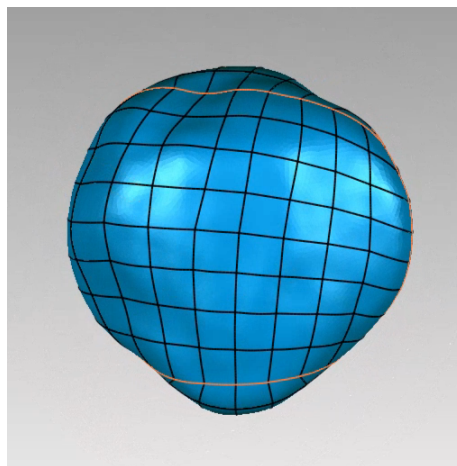


Figure 5. Patella Patch Layout

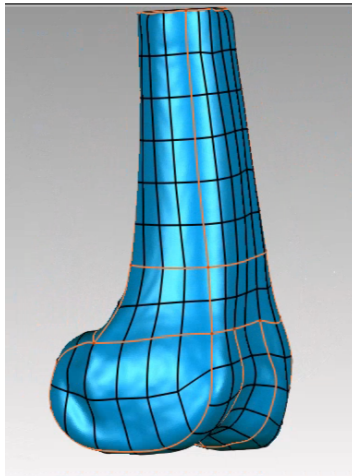


Figure 6. Femur Contour and Patch Layout

Each patch was manually reshuffled as needed until it met the desired standards. Once patch layout was finalized, the Construct Grids command was used to further subdivide the patches, and the Fit Surfaces command was employed to generate the final NURBS surfaces. These completed NURBS models were then prepared for export as Parasolid files for subsequent finite element modeling.

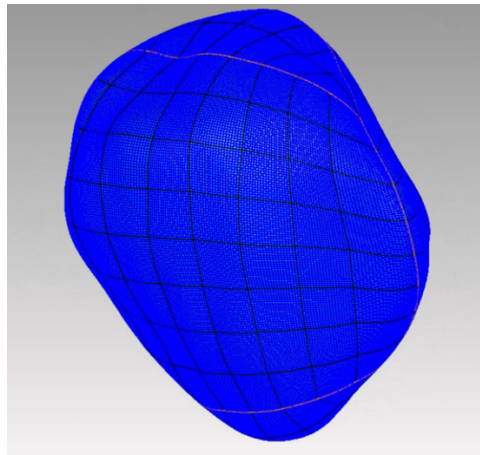


Figure 7. Constructed Grid on Patella Bone

4. Results

The work performed in both Materialise Mimics and Geomagic Wrap resulted in four complete CAD models of the bones in the right knee, based on CT data obtained from the National Institutes of Health Visible Human Project (National Library of Medicine, 2021).

Figure 8 displays the front and back views of the patella model. The patella was constructed using four contours, producing a patch layout that was conducive to forming square patches and a neat grid structure.

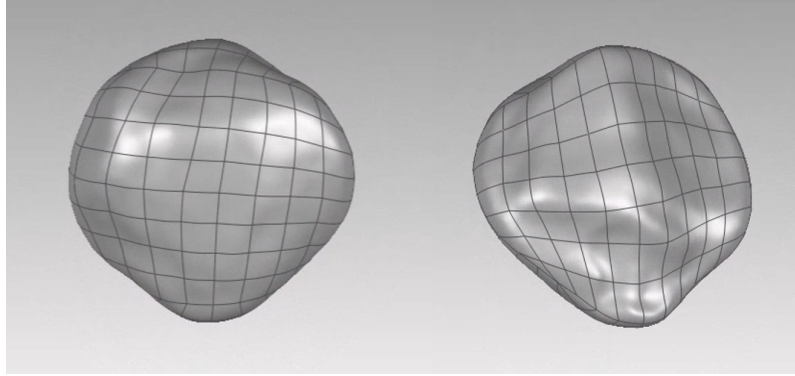


Figure 8. Front and Back of Finished Patella Model

Figures 9 and 10 present multiple views of the distal femur model. This model includes the medial and lateral condyles of the knee and extends partially up the femoral shaft. In total, 17 contours were required to create a clean and accurate NURBS surface. While the femur was challenging to model due to its complex geometry, the final NURBS result was of high quality.

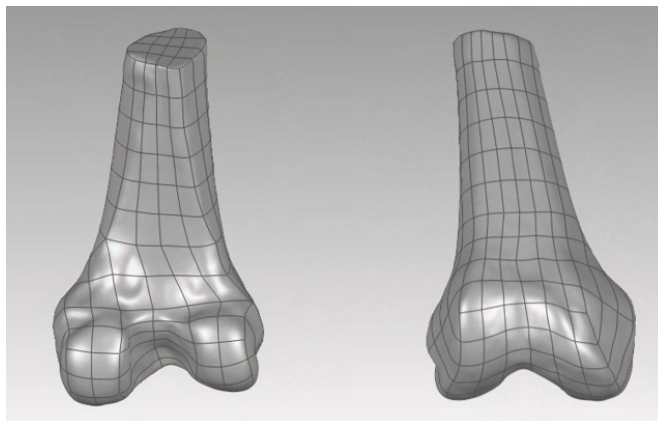


Figure 9. Anterior And Posterior View Of NURBS-Based Surface Model of Distal Femur Including Condyles and A Portion of Femoral Shaft

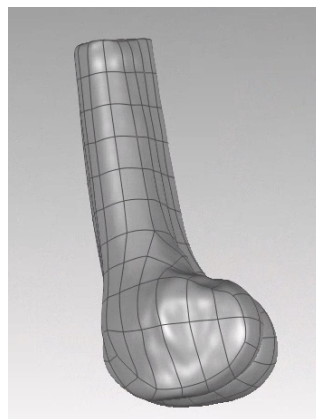


Figure 10. Lateral View of NURBS-Based Surface Model of Distal Femur

The NURBS-based surface models for the tibia and fibula are shown in Figures 11 and 12, respectively. The tibia's shape—characterized by a large surface area proximally that tapers significantly distally—made it the most challenging bone for generating a clean patch layout, ultimately requiring 17 contours. Although the fibula is smaller, it still required 14 contours but presented fewer modeling challenges overall.

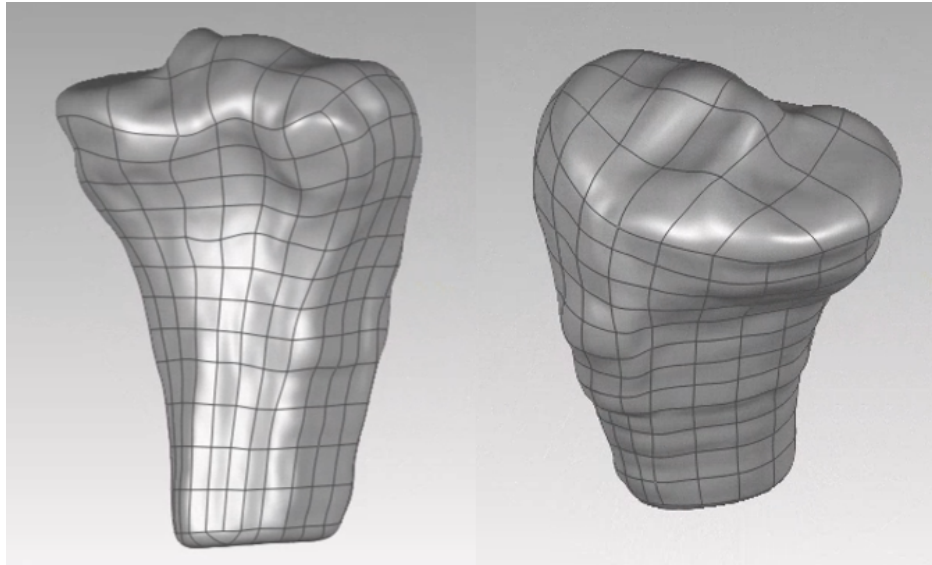


Figure 11: Anterior and Posterior Views Of NURBS-Based Tibia Model

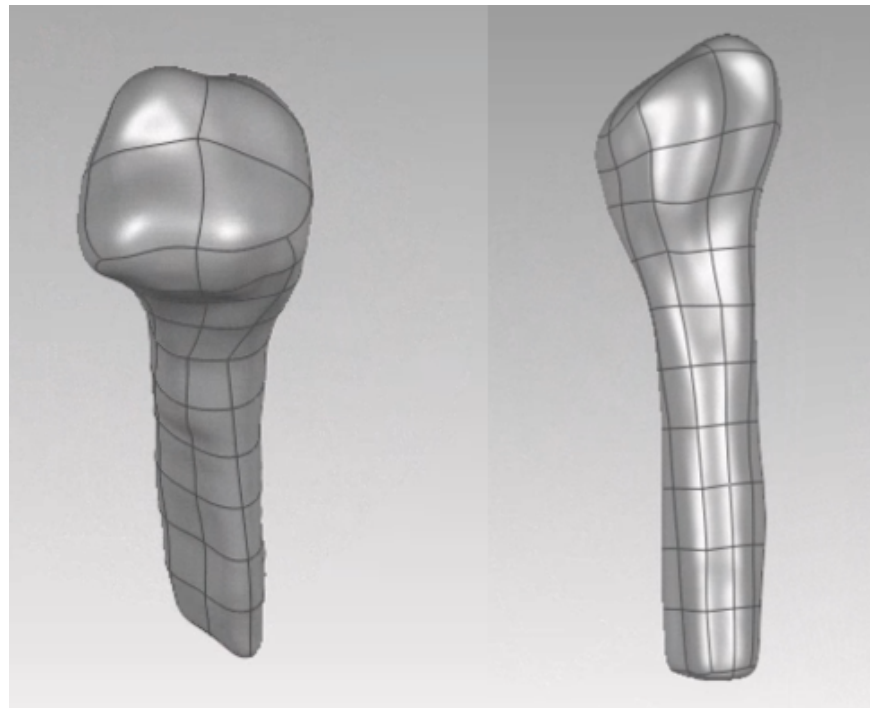


Figure 12: Oblique Posterior and Lateral Views Of NURBS-Based Fibula Model

5. Discussion

Due to the complex shapes of the different knee bones, achieving high quality patch grids across each model was challenging. For example, because only a single contour covered the top of the tibia—and its geometry was highly irregular—certain patches included curves, ridges, and bumps that were non-uniform with the rest of the surface. These challenges are consistent with prior work on developing finite element meshes of free-form anatomical structures such as the femur, where achieving uniform mesh quality over irregular geometry was similarly difficult (Schonning et al., 2009). This study applied the workflow to all major bones of the knee and initiated cancellous bone modeling, providing a more comprehensive reconstruction than our prior femur-focused work.

Ideally, the models would mimic a simple cubic structure, where each side supports a clean, square patch grid. Thus, the modeling approach focused on treating each bone segment as "cube-like" where possible, carefully arranging points and contours to achieve rectangular patch layouts. Although the anatomical shapes deviated significantly from cubic simplicity, with careful refinement, the patches were made as rectangular and uniform as possible, resulting in mostly optimal wraps.

Because the CT scan threshold had to be expanded to eliminate gaps in the bone structures, it is possible that the modeled bones include slightly greater thickness or material volume than in reality. This increase in thickness varies through the model from one to a few voxels in size. However, the general anatomical shapes were preserved, ensuring that overall modeling accuracy remains appropriate for structural analysis.

In addition to modeling the cortical bone surfaces, an attempt was made to model the cancellous bone within the distal femur, proximal tibia, fibula, and patella. The same CT slices used for the cortical models were reprocessed in Mimics using a lower threshold range (148–661 HU) to capture the density of cancellous bone. However, due to the lack of a solid, well-defined exterior surface, it quickly became apparent that surfacing in Geomagic Wrap would not be feasible for these structures. Aside from removing some excess geometry from the fibula, no further cleaning or editing was conducted. Consequently, the resulting cancellous bone models, shown in Figure 13, reflect primarily the raw output from Mimics and highlight the challenges associated with accurately modeling spongy internal bone structures.

The resulting models facilitate improved anatomical understanding and have potential applications in prosthetic design, biomedical research, and orthopedic interventions. Future work will involve developing more advanced segmentation and surfacing techniques tailored specifically for cancellous bone. Alternative approaches, such as voxel-based meshing or hybrid modeling that combines cortical and cancellous structures, may enable successful representation of internal bone anatomy for subsequent analysis.

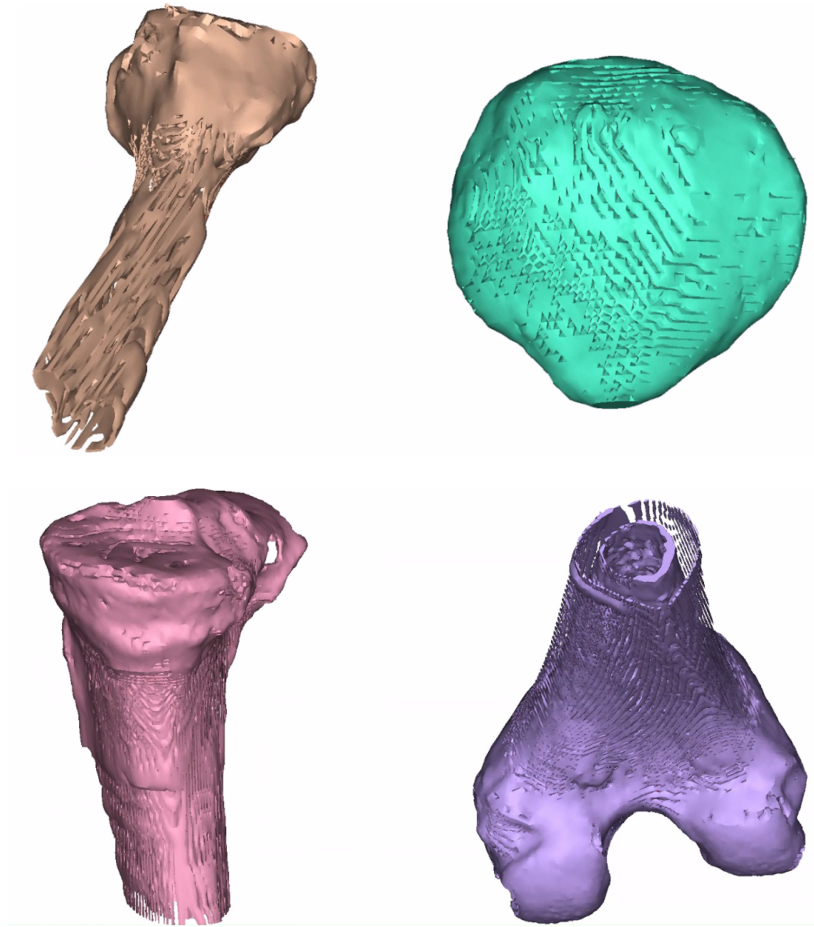


Figure 13: Cancellous Bone Models

6. Disclaimer Statements

Funding: No external funding was received for this research. Institutional support, including access to licensed software and salary support, was provided by the University of North Florida.

Conflict of Interest: None

7. References

- 3D Systems, Inc. (2024). Geomagic Wrap (Version 2021.0) [Computer software]. Author.
<https://www.3dsystems.com/software/geomagic-wrap>
- Ackerman, M. J. (1998). The Visible Human Project. *Proceedings of the IEEE*, 86(3), 504–511.
<https://doi.org/10.1109/5.662875>
- Harrysson, O. L. A., Cansizoglu, O., Marcellin-Little, D.J., Cormier, D. R., & West, H.A., Direct metal fabrication of titanium implants with tailored materials and mechanical properties using electron beam melting technology, *Materials Science and Engineering: C*, vol. 28(3), pp. 366-373, 2007.
<https://doi.org/10.1016/j.msec.2007.04.022>
- Harrysson, O. L. A., Hosni, & Y. A., Nayfeh, J. F., Custom-designed orthopedic implants evaluated using finite element analysis of patient-specific computed tomography data: femoral-component case study, *BMC Musculoskeletal Disorders*, vol. 8, 2007. DOI: [10.1186/1471-2474-8-91](https://doi.org/10.1186/1471-2474-8-91)

- Kladovasilakis, N., Tsongas, K., & Tzetzis, D., Finite Element Analysis of Orthopedic Hip Implant with Functionally Graded Bioinspired Lattice Structures, *Biomimetics*, vol. 5, article 44, 2020. <https://doi.org/10.3390/biomimetics5030044>
- Knapp, A., Schonning, A., Stagon, S., & Livingston, B. (2016). Development of 3D geometry of the foot for FE plantar fasciitis study. *Journal of Management and Engineering Integration*, 9(1), 1–6. https://www.journalmei.com/files/ugd/f76c8e_66525834427f4f9f967775902a8ea6a4.pdf
- Mahmoud, D., & Elbestawi, M. A., Lattice Structures and Functionally Graded Materials Applications in Additive Manufacturing of Orthopedic Implants: A Review, *Journal of Manufacturing and Materials Processing*, vol. 1, article 13, 2017. <https://doi.org/10.3390/jmmp1020013>
- Materialise NV. (2024). *Mimics Medical* (Version 25.0) [Computer software]. Author. <https://www.materialise.com/healthcare/mimics>
- Meglioli, M., Naveau, A., Macaluso, G. M., Catros, S. 3D printed bone models in oral and craniomaxillofacial surgery: a systematic review, *3D Printing in Medicine*, vol. 6, article 30, 2020. <https://doi.org/10.1186/s41205-020-00082-5>
- Mercader A., Röttinger T., Bigdeli A., Lüth T. C., Röttinger H., A patient-specific 3D model of the knee to compare the femoral rollback before and after total knee arthroplasty (TKA), *Journal of Experimental Orthopaedics*, vol. 8, no. 2, 2021. DOI: [10.1186/s40634-020-00319-6](https://doi.org/10.1186/s40634-020-00319-6)
- National Library of Medicine. (2021, June 10). *Visible Human Project®: Female radiological images (normal CT)*. U.S. National Institutes of Health, Lister Hill National Center for Biomedical Communications. <https://data.lhncbc.nlm.nih.gov/public/Visible-Human/Female-Images/radiological/normalCT/index.html>
- Pitocchi, J., Wesseling, M., van Lenthe, G. H., and Pérez, M. A., Finite Element Analysis of Custom Shoulder Implants Provides Accurate Prediction of Initial Stability, *Mathematics*, vol. 8, no. 7, 2020. <https://doi.org/10.3390/math8071113>
- Ramavath D., Yeole, S. N., Kode, J. P., Pothula, N., Devana, S. R., Development of patient-specific 3D printed implants for total knee arthroplasty, *Exploration of Medicine*, vol. 4, pp. 1033-1047, 2023. <https://doi.org/10.37349/emed.2023.00193>
- Richardson, R., Richardson, M., Quijano, B., Wong, E., & Schonning, A. (2012). Development of CAD and FE models of a transfemoral limb prosthetic interface. *Journal of Management and Engineering Integration*, 5(1), 56–61. https://www.journalmei.com/files/ugd/f76c8e_0638587f0b424a91897cb9d2b5c8fbbf.pdf
- Schonning, A., Oommen, B., Ionescu, I., & Conway, T. (2009). Hexahedral mesh development of free-formed geometry: The human femur exemplified. *Computer-Aided Design*, 41(8), 566–572. <https://doi.org/10.1016/j.cad.2007.10.007>
- Surapureddy, R., Schonning, A., Stagon, S., & Kassab, A. (2016). Predicting pressure distribution between transfemoral prosthetic socket and residual limb using finite element analysis. *International Journal of Experimental and Computational Biomechanics*, 4(1), 1–12. <https://doi.org/10.1504/IJECB.2016.081746>
- Sharma, M. & Soni, M., Direct metal laser sintering of Ti6Al4V alloy for patient-specific temporomandibular joint prosthesis and implant, *Materials Today: Proceedings*, vol. 38, pp. 333-339, 2021. <https://doi.org/10.1016/j.matpr.2020.07.417>
- Teichtahl, A. J., Wluka, A. E., Strauss, B. J., Wang, Y., Berry, P., Davies-Tuck, M., Cicuttini, F. M. The associations between body and knee height measurements and knee joint structure in an asymptomatic cohort. *BMC Musculoskeletal Disorders* 13, 19 (2012). <https://doi.org/10.1186/1471-2474-13-19>
- Vasiliadis, A. V., Giovanoulis, V., Maris, A., Chytas, D., Katakalos, K., Paraskevas, G., Noussios, G., Vassiou, A. Finite element analysis of the knee joint: a computational tool to analyze the combined behavior after treatment of torn ligaments and menisci, *SICOT-J*, vol. 10:45, 2024. DOI: [10.1051/sicotj/2024039](https://doi.org/10.1051/sicotj/2024039)
- Zanjani-Pour, S. Giorgi, M., Dall'Ara, E., Development of Subject Specific Finite Element Models of the Mouse Knee Joint for Preclinical Applications, *Frontiers in Bioengineering and Biotechnology*, vol. 8, 2020. <https://doi.org/10.3389/fbioe.2020.558815>

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APPLYING MODEL-BASED SYSTEMS ENGINEERING MODELS FOR ENHANCING OPERATIONAL EXCELLENCE

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Abstract

Model-Based Systems Engineering is becoming more common in systems design efforts. These tools were derived originally from the Unified Modeling Language borrowed from the information systems development toolkit. The SysML models are those most commonly used for modeling and designing systems. Systems Engineering tools can provide the view of the system, the scope of the processes to be improved and standardize models to design, improve and automate processes within Operational Excellence programs. Basic systems engineering tools including SIPOC, Value Chain, Functional Decomposition Diagram, and Process Architecture Maps will be described. Two advanced systems engineering models from the SysML models will be described, use case and activity diagrams. Examples from a hospital's emergency services system will be provided. The basic and advanced models can standardize and improve the organization's operational excellence program.

Keywords: *Model-Based Systems Engineering; Activity Diagram; Use Cases; Systems Engineering.*

1. Introduction

Systems engineering, and systems thinking is a body of knowledge brought together from multiple disciplines to understand the patterns, elements, structures, behaviors and integrations that help to design a system. In our context in this paper, a system from an operational excellence perspective and the people, processes and technology that we design and improve to enhance productivity and the quality of how work is performed. One of the first researchers to define a system, was Bertalanffy (1968) working in the biological systems discipline. He defined a system very simply, as a set of elements in interaction. (Bertalanffy 1968). INCOSE (2015) defines a system as: *Any set of related parts for which there is sufficient coherence between the parts to make viewing them as a whole useful.* They define an engineered system as: *An engineered system defines a context containing both technology and social or natural elements, developed for a defined purpose by an engineering life cycle.* (INCOSE, 2015)

In the system lifecycle methodology, the system is architected, and the requirements are elicited from the systems' users or customers. There are many systems engineering tools that can enhance operational excellence tools to design processes and systems. Model Based Systems Engineering is an approach to provide automated electronic models to describe a system through many different diagrams and models that exist in a centralized and standardized repository for use and re-use by the modelers. These models can be used to provide different views to show structure and behavior of the systems elements, as well as their interactions. SysML is the Systems Modeling Language whose models were derived originally from the software body of knowledge that applied Object-Oriented design and programming, and the Unified Modeling Language. Nine important models are commonly categorized as models that are used to model systems, across the system acquisition

lifecycle. There are many traditional tools used to model, design and improve processes to enhance operational excellence in organizations. The goals of this paper are to:

1. Demonstrate how the integration of several systems engineering tools can provide a systems view of operational excellence initiatives.
2. Provide examples of basic systems engineering tools that provide systems view which include the SIPOC, value chain, functional decomposition model, and process maps.
3. Demonstrate how to use advanced Systems Modeling Language (SysML) models to extend the basic process modeling tools to integrate system and process requirements including Activity diagrams, and Use Case diagrams.

The paper will include in the next section a literature review describing Model-Based Systems Engineering which provides the foundation for the systems engineering models that will be described in the Methodology and Results sections. Conclusions and Future Work concludes the paper.

2. Literature Review

Furterer (2022) discusses three dimensions of integration of Model Based Systems Engineering (MBSE) including: 1) between phases of the life cycle by integrating behaviors and structures across the phases; 2) between levels of detail within models – such as decomposing functions into more detailed functions; and 3) integration between elements to the system – showing connections within elements of a model such as a class diagram or an Internal Block Diagram. The models show the integration of elements between each phase of the life cycle by integrating concepts, stakeholders and risk in the concepts phase, to the requirements and architecture elements to derive and elicit requirements. The requirements in use case diagrams may be integrated to specifications in the design phase, as well as to integration and interface elements in detailed design. The use cases in the requirements phase can be used as the foundation for test cases in the implementation, verification and validation phases, through to a deployed integrated system. The models show integration from high-level functions to lower level more detailed functions. Lastly the models also identify connectivity between elements, sub-systems, and systems. (Furterer, 2022)

MBSE requires a change in thinking for the organization adopting these automated modeling approaches. The culture and thinking moves from a modeling approach based on documents versus integrated models that demonstrate traceability and multiple views. Requirements identified within a requirements model, can be tied to specifications within the Block Definition Diagram (BDD) and an Internal Block Diagram (IBD) within the design phase. The use case diagrams and narratives can be used to develop test cases and generate results within the verification and validation phases. Additionally, organizations are beginning to connect simulation and other modeling tools to the systems models. According to Madni and Sievers (2018) the value of MBSE comes from the system-related information being stored in a centralized and configuration managed repository. The software repository should enable the architected and interconnected capability of the system elements and models. It should also ensure alignment to the modeling language and standards, and incorporate error identification as part of the information system. Much research still needs to be performed, as Henderson and Salado (2021) found that many of the benefits of MBSE are in the expectations, not within empirical evidence.

3. Methodology

The activities performed and the tools applied in the requirements and architecture phase in

designing a system are shown in Table 1 (Furterer, 2022). In the “Develop Logical Architecture” activity, the Logical Architecture tools include the SIPOC, Value Chain and Functional Decomposition Model, and Use Case Diagrams to provide a conceptual architecture of a system. These same tools can be used to design the architecture for designing or improving processes within the organization’s operational excellence program.

Table 1. The Vee System Lifecycle Phase 2 – Requirements and Architecture Activities, Tools and Principles

Vee Phase	Activities	Tools	Principles
Phase 2: Requirements & Architecture	• Develop Logical Architecture • Develop Business requirements • Develop system requirements	Logical Architecture: • Value Chain & Functional Decomposition; Class Diagram Requirements: • Business requirements; Process Scenarios; System requirements • Use Case Diagram	• System dynamics (behavior, system elements) • Cybernetics (information flow) • Systems thinking • Abstraction • Views

3.1. Basic Systems Engineering Tools for Operational Excellence

The logical architecture tools that are developed in this phase that can be used to design processes are:

- SIPOC – is a model that frames the scope of the processes to be designed or improved by drawing the boundaries of the processes included in the system.
- Value Chain – a model that describes the value adding and activities that support them to be performed by the system, as a set of processes.
- Functional Decomposition– a model that decomposes the system functions to provide a taxonomy or inventory of the functions that are performed in the system.
- Use Case Diagrams – a model that describes the uses or functions and the actors (people or automated systems) that interact with and perform the systems.

Figure 1 (Furterer, 2022), shows the relationships between the tools of the system architecture including the SIPOC process steps, the Value Chain activities, the functions in the Functional Decomposition, the uses or functions in the Use Case Diagrams, and the process maps.

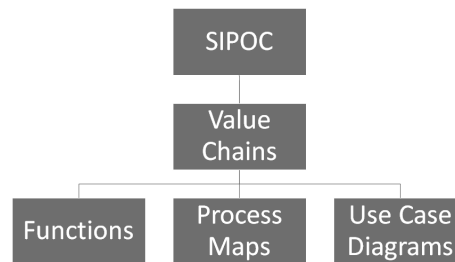


Figure 1. Relationship Between System Architecture Tools

3.1.1 SIPOC (Furterer, 2022)

The SIPOC is a useful tool in this phase to help define the boundaries of the system from a functionality, stakeholders and information perspective. SIPOC stands for suppliers, inputs, process, outputs and customers. The SIPOC shows the connectedness between the customers and suppliers, the information that they provide or are provided to them, and the information that they use within each process step. The process steps in the SIPOC become the first level value chain activities in the value chain model and in the functional decomposition model.

3.1.2 Value Chains

The value chain is a chain of activities that provide value to your customer and enable competitive advantage. The concept of a value chain was first described and popularized by Michael Porter (Porter, 1985). Value chains consist of value activities which are the critical activities performed by an organization to meet the needs of the customers, while support activities support these value activities (Furterer, 2022).

3.1.3 Functional Decomposition

The next model that we will describe is the Functional Decomposition Model. The Functional Decomposition Model (FDM) defines the hierarchical structure of the functions and the processes that they include. A Functional Decomposition Model provides a taxonomy or inventory of the key functions of our system and processes. The organization of the model should use the same high-level functions from the value chain activities and then decompose the functions of the system. This enables modeling of the functions into further detail within process maps. A system function is usually described in a noun-verb pairing, such as 'Patient Registration' (Furterer, 2022).

Steps to develop the FDM:

1. Identify the scope of the system to be modeled through application of the Value Chain model
2. Identify the highest-level functions within the Value Chain activities, and transfer these to the first level of the FDM. Use, using noun-verb names
3. Decompose the first level functions into lower-level functions, again using noun-verb names
4. Stop when there becomes a natural sequence of the activities, usually 2 to 4 levels. Next is the time to use a process map.

3.1.4 Process Architecture Map

A process map is a graphical display of steps, events, and operations that make up a process. A process map helps us to document, understand, measure and control a process. During development of the process map, the process owners who are engaged in performing the process should be engaged in walking through process scenarios and gaining agreement that the process map represents the actual process. The process map can be used to document the current existing process or the future state process that incorporates opportunities for improving and automating the process. The author developed a process architecture map (PAM) that incorporates process architecture elements to help automate and improve processes, including: the role that performs each activity, the information and technology used to perform the activity (Furterer, 2022).

3.2. Advanced Systems Engineering Modeling Tools

3.2.1 Use Case Diagram

Use cases diagrams are a graphical representation of use cases, or functions developed and viewed from the users' perspective. They are used to generate the system's requirements including how the process will work. There are several advantages of use case diagrams and the narrative representation of use case diagrams called the use cases. The requirements are placed in the context of the users' work and their domain knowledge. They are easy for most users to understand, because they use the users' own vocabulary. These diagrams show why the system and the process is needed, along with the interactions between the functions or uses and the actors (people or automated systems) (Furterer, 2022).

3.2.2 Activity Diagram

An activity diagram is a dynamic view of the system, and shows the behavior of the system or process. It is good at expressing the flow of objects, where objects can be matter, energy or data. This diagram focuses on how the objects can be accessed and modified in an execution of that behavior during system operation. It is uniquely capable of expressing continuous system behaviors. The actions in the diagram express the order in which they are performed, and can express which structure performs each action. An activity diagram can be used when you need to communicate with stakeholders about the system or processes, when you need to communicate with other team members to capture the expected behaviors of the system's internal parts. The activity diagram is not tied to any particular stage of the system or process design lifecycle. The frame or boundaries of the activity diagram is abbreviated in SysML models as "act". The only allowable element in the diagram is an activity. The frame represents a single activity that you have defined somewhere in your models, such as in the functional decomposition or a use case diagram. An activity is a kind of behavior. The activity diagram can contain a set of name elements that includes nodes (start, end, merge, etc.) and edges. Once the activity diagram is modeled, it can be used to extract process requirements.

4. Results

Examples to demonstrate the use and value of the basic and advanced systems engineering tools that can be used to model, design and improve processes are discussed in the results section.

4.1. Basic Systems Engineering Tools

4.1.1 SIPOC

The SIPOC starts in the middle with the process steps that illustrate the scope of the process to be designed or improved. It starts with registering the patient when they arrive at the Emergency Department (ED). The patient is triaged and receives an acuity level which dictates the priority of the patient to be moved to an ED room. The patient is treated, and diagnosed, which may include labs, imaging, and other examinations. The ED Physician disposes the patient to admit or discharge the patient. The inputs and outputs are the high-level information that is used to perform the process activities. The suppliers provide the inputs to the process, and the customers receive the outputs from the process steps. The SIPOC tends to have a flow in the process steps from top to bottom, and many times the customers of the prior step become the suppliers of the next step. The SIPOC for emergency services is shown in Table 2.

Table 2. SIPOC for Emergency Services

Suppliers	Inputs	Processes	Outputs	Customers
Patient Physicians	Referral Patient Information	Register Patient	Patient Registration information	Triage nurse
Triage Nurse Patient	Patient information	Triage Patient	Acuity level Room priority	Emergency Department (ED) Nurse
Patient Physicians Nurses Medical Staff Admissions	Patient information Orders	Treat Patient	Test results	ED Physician
ED Physician Patient	Test results	Diagnose Patient	Diagnosis	Patient ED Nurse Medical Staff
Patient ED Nurse Medical Staff	Diagnosis	Disposition Patient	Disposition Discharge or Admit orders	Patient Medical Staff
Patient Medical Staff	Disposition Discharge or Admit Orders	Patient is Discharged or Admitted	Patient Discharge information Patient Admission Information	Patient Medical Staff

4.1.2 Value Chain

The Emergency Services Value chain is shown in Figure 2 (Furterer, 2014).

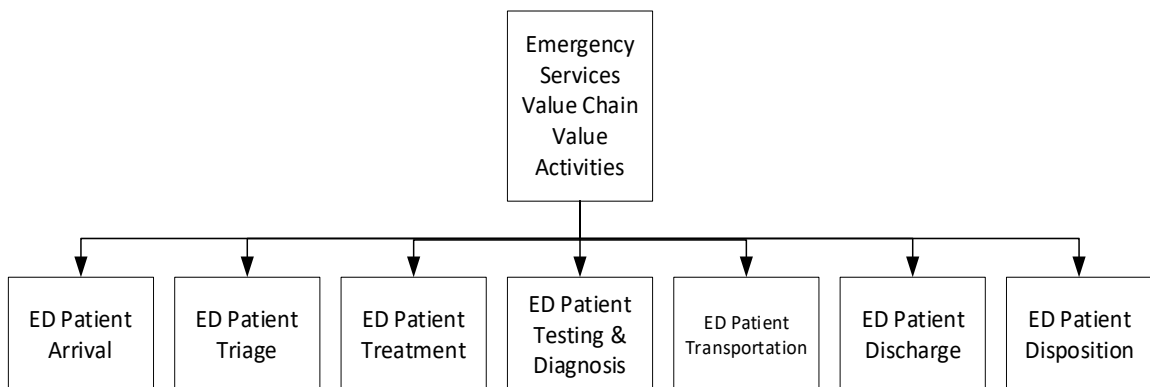


Figure 2. Emergency Services Value Chain

4.1.3 Functional Decomposition Model

The Functional Decomposition Model (FMD) starts with the Value Chain activities as the level one functions in the FDM. They are then decomposed into at least a second level of functions, and sometimes three, depending upon the complexity of the system to be modeled. A stopping point rule of thumb is when there starts to be a natural sequence to the functions, the modeler can then move to a process map. The Emergency Services FDM is shown in Figure 3 (Furterer, 2014).

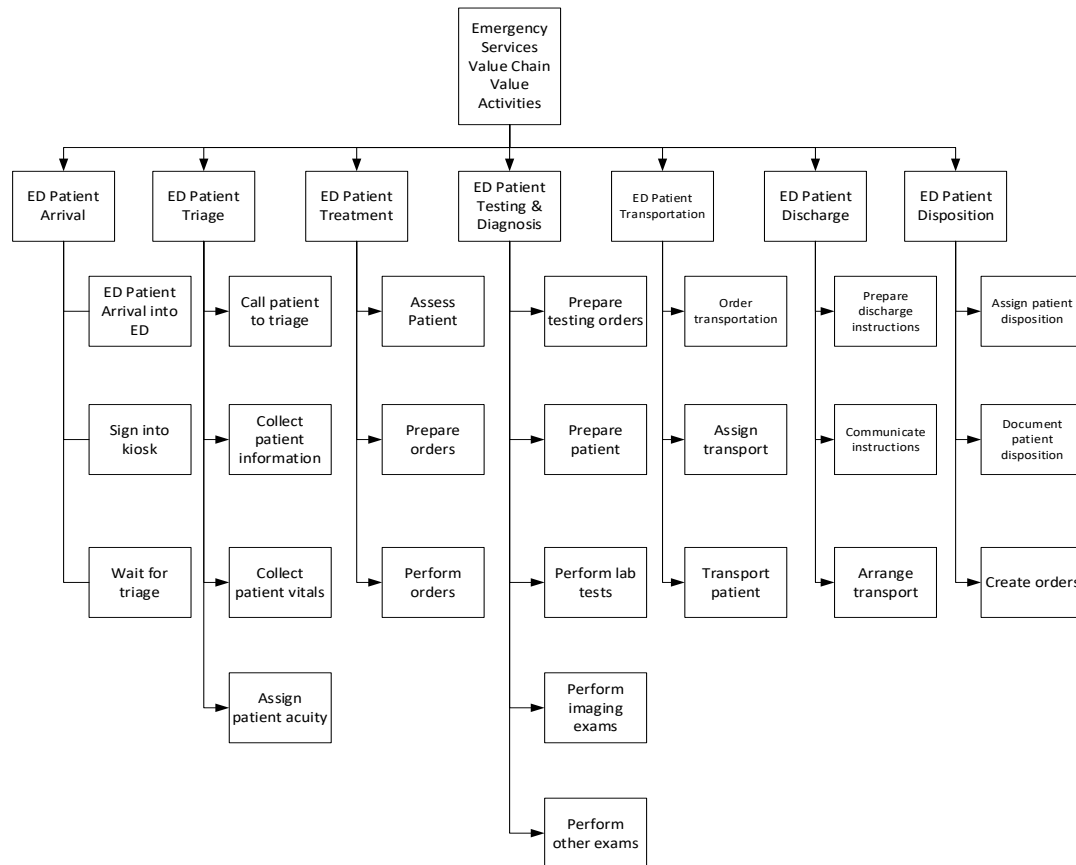


Figure 3. Emergency Services Functional Decomposition Diagram

4.1.4 Process Architecture Map

The Emergency Services Process Architecture Map describes the process and is generated through development of process scenarios or storyboarding, where the users of the process are facilitated through these scenarios to design or improve the processes. The process requirements for designing or improving the processes tend to “fall of the page” if these are done in detail. The PAM architecture cover page is shown in Figure 4, and the Process Map portion is shown in Figure 5 (Furterer, 2014). The architecture collected includes the roles, information and technology used or to be used in the process. The flow starts at the top left and moves to the right and then down the page. The rectangles are the activities. Decision diamonds represent decisions that separate into two paths. The ovals show start and end points. The circles connect the flow from one line to the next to avoid crossing arrows. A “D” symbol shows delays or waits in the process to identify opportunities for improvement.

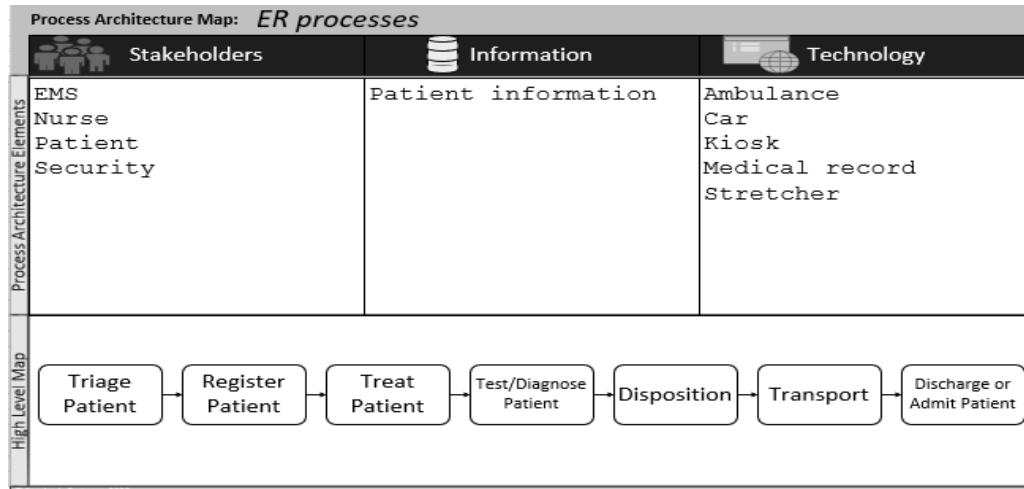


Figure 4. Emergency Services Process Architecture Cover Page

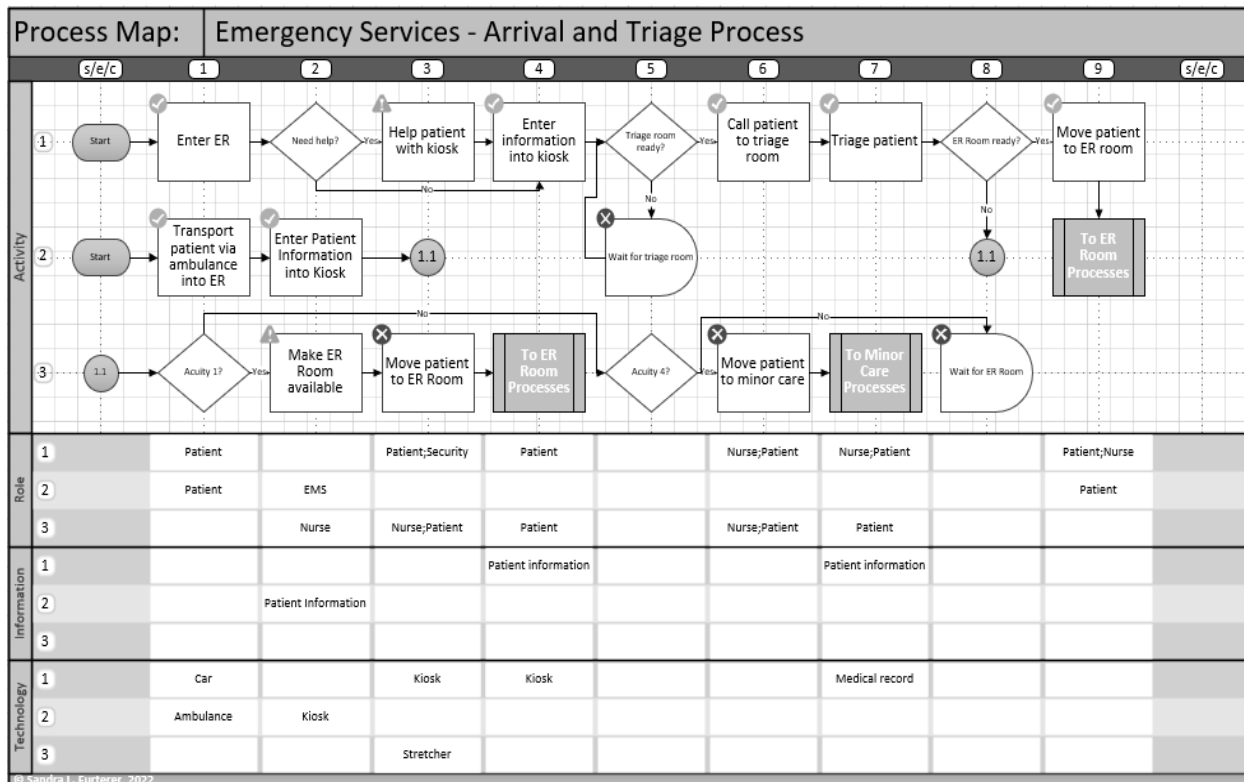


Figure 5. Emergency Services Process Architecture Map

4.2. Advanced Systems Engineering Modeling Tools

The two advanced systems engineering models that will be demonstrated are the use case diagram and the activity diagram.

4.2.1 Use Case Diagram

The Emergency Services Use Case Diagram for the triage functions is shown in Figure 6. The ovals are the functions, which are the second level functions from the FDM. The actors (people shapes) can be people in roles (ED Patient or ED Nurse) or can be automated systems (ED medical system). The arrows show the interaction between the actors and the functions. Interaction should not be shown to occur directly between actors, but between the actors and the functions.

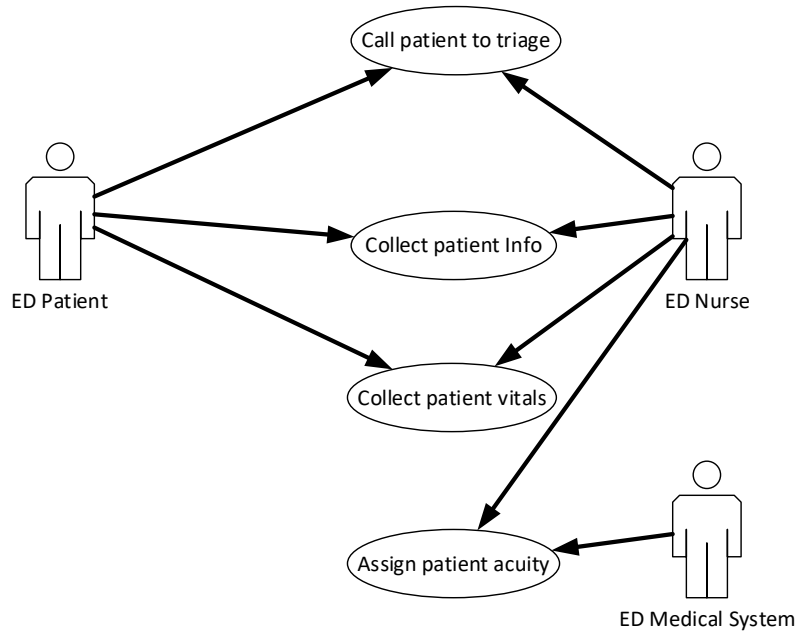


Figure 6. Emergency Services Use Case Diagram

4.2.2 Activity Diagram

The Emergency Services Activity Diagram is similar to a process map, but typically flows from top to bottom. The nodes control flow such as with the initial activity which starts the activity where the patient arrives. The first diamond shows flow going in two directions for when the patient needs help entering their information into the kiosk, or the patient entering their information without assistance. The second diamond represents a merge of the two paths to one, where the patient moves to the triage action. The third diamond shows the flow splitting again where the patient can either be assigned a regular ED room, or be moved to minor care, based upon the acuity assigned in the triage action. The activity diagram is quite powerful to illustrate flow, actions, and the logic that is used to move the patient through the system. This can be used to automate the flow as well. The Emergency Services Activity Diagram is shown in Figure 7. The basic and advanced systems engineering tools help to identify process requirements for improving and automating processes in the organizations operational excellence program. The standard notation and use of the models helps increase understanding, consistency and quality of these modeling techniques and the outputs from the modeling effort.

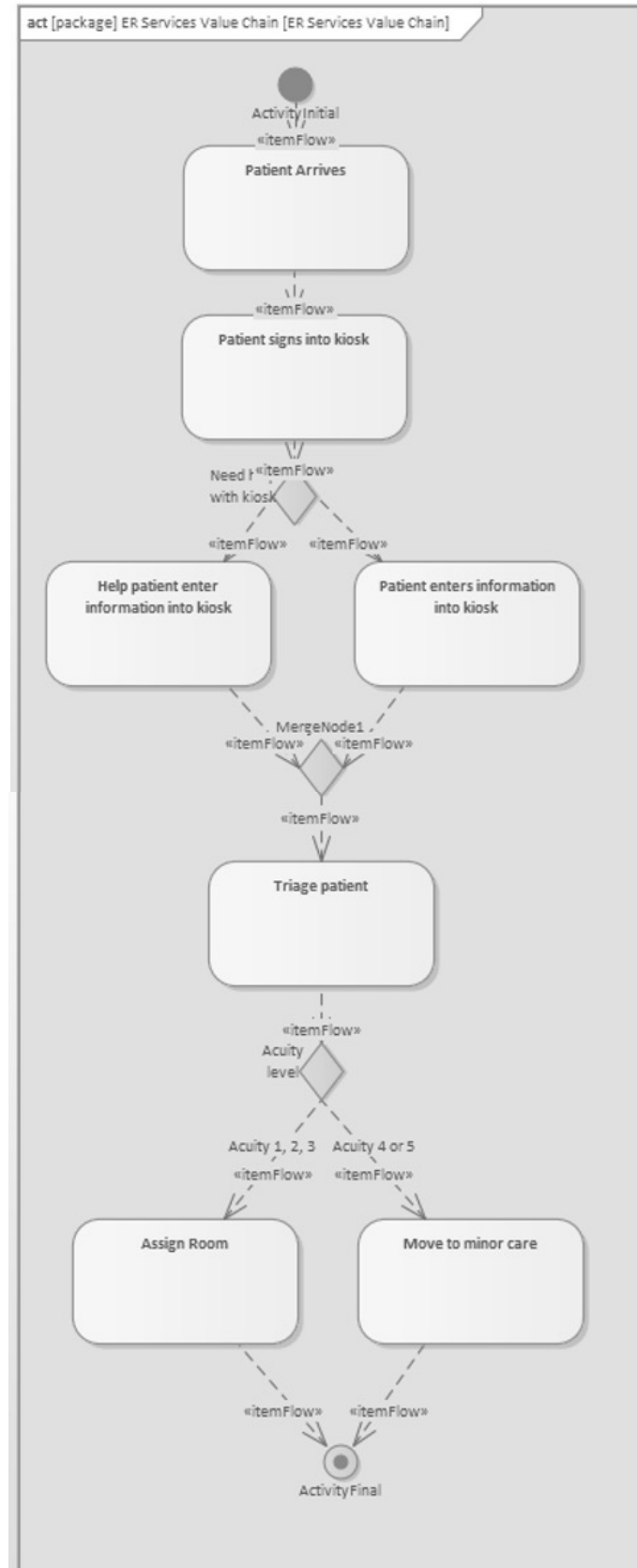


Figure 7. Emergency Services Activity Diagram

5. Conclusions and Future Work

The basic and advanced systems engineering modeling tools are powerful tools to enhance operational excellence in organizations. Many process design and improvement analysts most likely have used process maps to understand and improve processes. However, the basic systems engineering tools provide a scope and systems view of the process modeling efforts. The advanced tools provide a standardized modeling language to use to improve and automate the organization's processes. Future work can be to incorporate additional SysML modeling for process design and improvement and to increase the types of numbers of case studies where these models are applied.

6. Disclaimer Statements

Funding: None

Conflict of Interest: None

7. References

- Bertalanffy, L. V. (1968). *General system theory: Foundations, development, applications*, rev. ed., New York: Braziller.
- Furterer, S. L. (2014). *Lean six sigma case studies in the healthcare enterprise* (pp. 379-384). London, UK:: Springer. https://doi.org/10.1007/978-1-4471-5583-6_3
- Furterer, S. (2021). *Systems Engineering: Holistic Life Cycle Architecture Modeling and Design with Real-World Applications*. CRC Press.
- Henderson, K., & Salado, A. (2021). Value and benefits of model-based systems engineering (MBSE): Evidence from the literature. *Systems Engineering*, 24(1), 51-66.
- International Council on Systems Engineering. (2015). *Systems engineering handbook: a guide for system life cycle processes and activities*. Wiley.
- Madni, A. M., Spraragen, M., & Madni, C. C. (2014, October). Exploring and assessing complex systems' behavior through model-driven storytelling. In *2014 IEEE International Conference on Systems, Man, and Cybernetics (SMC)* (pp. 1008-1013). IEEE.
- Porter, M. E. (1980) *Competitive Strategy: Techniques for Analyzing Industries and Competitors*. New York: Free.

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INSTRUCTIONAL LEAN MANUFACTURING LAB DESIGN USING SMED

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Abstract

Lean manufacturing tools such as 5S, Single-Minute Die Exchange (SMED), pull vs. push and Kanban system, etc., are practical tools that help eliminate waste, increase efficiency, and improve quality in various manufacturing and other systems. In higher education, these tools can be taught to students in a traditional lecture-style model or illustrated as lab activities with hands-on simulation. In the undergraduate manufacturing engineering program under study, lean manufacturing concepts are taught in a Manufacturing Process Planning course. This study presents a tool kit design that provides an instructional learning experience on the principles and tools of lean manufacturing through hands-on activities/simulation that can be easily incorporated into the course curriculum. This project specifically focuses on developing and designing a traditional assembly vs. SMED assembly with the appropriate instruction manuals to help the students connect the theory and practice of this important lean concept. A t-shirt press process was proposed to illustrate this learning experience. Two t-shirt press machines were designed/modified for this project's purpose. One machine followed a traditional press process with fasteners and connectors, while the other machine was modified to incorporate SMED. Additionally, the machines were accompanied by examples of different levels of work instructions to demonstrate the importance of quality work instructions, an essential aspect of lean manufacturing, which is another topic covered in this class.

Keywords: *SMED; Process Planning; Instructional Lab.*

1. Introduction

Throughout the manufacturing industry, changeover and downtime are consistent and significant sources of time waste (one of the seven classic Muda) in production. Utilizing the Single Minute Exchange of Die (SMED) principle has significantly improved this changeover and downtime over the years. In general, SMED follows a few general guidelines:

- Minimize all internal elements (steps that must be completed while the machine is stopped).
- Complete external elements while the machine is running.
- Streamline the process whenever possible.

This study presents a toolkit design that provides an instructional learning experience on the principles and tools of lean manufacturing through hands-on activities and simulations that can be easily incorporated into the course curriculum. The project specifically focuses on developing and designing a traditional assembly versus a SMED assembly, accompanied by instruction manuals that

help students connect theoretical concepts with practical applications. SMED was chosen as the starting point for this effort because it offers a clear, measurable impact; reducing setup times in a way that the students can immediately observe and quantify, making it an effective gateway into lean thinking. This initial tool sets the foundation for a long-term project to build an instructional Lean Manufacturing Lab at WWU, where the research team envisions 10 interactive stations simulating production with a 1-minute takt time using Lego-based kits. Each station will highlight a different lean concept (e.g., Kanban, 5S, continuous flow), allowing students to rotate through challenges in a gamified and interactive environment.

2. Literature Review

The Single-Minute Exchange of Dies (SMED) methodology, introduced by Shigeo Shingo in the 1950s, significantly transformed manufacturing by greatly reducing setup times, consequently boosting production efficiency and flexibility (Shingo, 1985). Central to the SMED approach is its focus on ergonomics and intelligent design within setup operations, emphasizing the strategic importance of these factors for operational efficiency and productivity enhancement (Jurik et al., 2020). In the current competitive global market, where manufacturers consistently strive to minimize costs and maximize efficiency, SMED emerges as an essential strategy. By shortening production cycles and reducing associated expenses, SMED not only enhances operational performance but also significantly improves product quality (Anand & Kodali, 2008; Jurik et al., 2020). The methodology fosters an organizational culture characterized by teamwork, precise organization, careful planning, and straightforward yet impactful process modifications. Such adaptability enables manufacturers to substantially reduce losses caused by frequent equipment changeovers, demonstrating SMED's effectiveness across various industries and sectors (Naik & Chakravorty, 2015; Anand & Kodali, 2008). A fundamental component of the SMED methodology involves systematically analyzing setup operations to identify and exploit opportunities for improvement (Naik & Chakravorty, 2015; Anand & Kodali, 2008).

SMED categorizes setup activities into internal and external operations: internal activities require equipment downtime (e.g., tool changes), whereas external activities (e.g., tool preparation and parameter setting) can be completed without stopping the machine (Anand & Kodali, 2008). The primary goal of SMED is converting as many internal tasks to external ones as possible. Techniques such as pre-assembling parts, introducing quick-release mechanisms, and standardizing setup processes effectively reduce machine downtime and enhance overall efficiency and operational flexibility (Hornakova & Jurik, 2020). Through accelerated and streamlined changeovers, SMED facilitates an agile manufacturing environment capable of quickly adapting to changing production demands with reduced lead times and enhanced cost-effectiveness. Aligning closely with lean manufacturing principles, SMED seamlessly integrates with Total Productive Maintenance (TPM) and continuous improvement frameworks, achieving documented setup time reductions between 25% to 85% (Anand & Kodali, 2008).

Recent studies have expanded the traditional SMED methodology by integrating Industry 4.0 technologies. Khakpour, Ebrahimi, and Seyed-Hosseini (2024) propose "SMED 4.0," utilizing IoT and machine learning to enhance sustainability and proactively manage defects during production. Toki et al. (2022) demonstrate SMED's effective application in Bangladesh's ready-made garments sector, significantly reducing setup times and enhancing production efficiency. Similarly, Rafael et al. (2023) combine SMED with Value Stream Mapping in the spring bed manufacturing sector, showcasing substantial efficiency improvements. Molla et al. (2024) further validate SMED's efficacy by demonstrating its impact on setup time reductions in electronics manufacturing. The versatility of SMED has led to its widespread adoption beyond its automotive origins, extending to sectors such

as electronics, pharmaceuticals, food and beverage, among others. This broad applicability underscores its effectiveness across diverse equipment and operational setups, reinforcing its transformative potential for global manufacturing practices (Jurik et al., 2020). Consequently, adopting SMED not only enhances efficiency and product quality but also provides manufacturers with a substantial competitive advantage in international markets (Naik & Chakravorty, 2015; Anand & Kodali, 2008). In conclusion, The SMED methodology represents a crucial innovation in manufacturing, significantly enhancing production efficiency and flexibility by optimizing setup operations. Its emphasis on ergonomic design and strategic task management supports manufacturers in effectively addressing challenges related to cost and efficiency. With proven successes across multiple industries and clear compatibility with broader lean manufacturing and continuous improvement principles, SMED stands as a vital strategy for achieving operational excellence and sustaining competitive advantage in today's manufacturing landscape.

3. Method

This study aimed to investigate the impact of a hands-on SMED lab activity on undergraduate engineering students' understanding of lean manufacturing concepts. The project was implemented within a Manufacturing Process Planning course that includes both lecture and lab components. The development of the lab followed a systematic methodology represented in the flowchart in Figure 1 below. This approach allowed students and faculty to collaboratively select an appropriate product for demonstrating SMED principles, while ensuring that the final design met pedagogical goals. To reinforce the instructional goals, students also created different levels of work instructions for each machine. These instructional artifacts became a secondary pedagogical tool, allowing students to experience the relationship between quality documentation and lean process design. Through this structured approach, the SMED lab experiment was developed to closely align with lean manufacturing principles and provided students with both a practical and conceptual understanding of changeover reduction strategies.

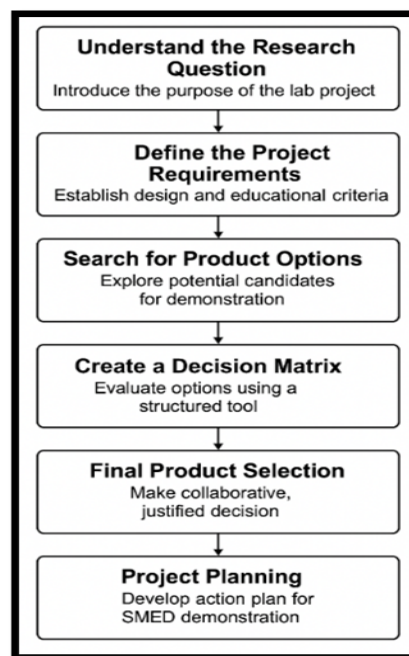


Figure 1. Flowchart of the Research Design Steps

3.1. Project Requirements

To guide the selection of an appropriate product and ensure the lab experience aligned with educational and safety goals, a clear set of project requirements was defined. These requirements addressed both instructional value and operational constraints. They were developed by faculty in collaboration with students and served as the foundation for the evaluation matrix used during product selection. The key requirements were as follows:

- No prior technical knowledge required for operation
- At least three modifiable features suitable for demonstrating SMED
- Simple and safe enough to be operated during class periods
- Portable, storable, and affordable for classroom use
- Clear visual and operational contrast between internal and external setup steps

These qualitative requirements were further refined into a set of measurable design metrics, as shown in table 1 below. These criteria ensured that the selected demonstration product not only met functional lean objectives but also complied with classroom safety standards, time availability, and budget constraints. The presence of multiple SMED changeover opportunities, ergonomic design, and accessible use by novices made the final design both educationally effective and operationally sound.

Table 1. Design Metrics

METRIC #	METRIC
1	The machine must have components that are safe for students to use
2	The machine must have minimal risk of physical collision with users
3	The machine must incorporate a safe exit
4	The total mass of the system
5	Total size/footprint
6	The fully assembled system must be ergonomically movable
7	The system must be relatively easy to store
8	The system must incorporate at least three SMED changeovers
9	The system must provide a learning experience for students
10	The project must remain affordable for the engineering department
11	The project must be completed before the due date
12	Budget
13	Time constraint

3.2. Product Options and Selection

After defining the project requirements and associated metrics, a variety of potential products were evaluated using a decision matrix. Each option was scored on a 1–5 scale across eight weighted criteria: safety and simplicity, SMED modification points, visual engagement, portability, cost, activity duration, system weight, and complexity. The weight factor for each criterion was defined to reflect its relative importance in the context of the lab. For instance, safety and simplicity of use were assigned the highest weight (0.20), while system complexity and setup time carried lower but still relevant weightings (0.05 each). Table 2 below presents the comparative scores for six product

candidates.

Table 2. Decision Matrix

Decision Matrix (Scale 1-5)	Design Criteria								Rating Factor (R.F)
	Safe & Simple to Use	Clear SMED Modification Points	Visual and engaging	Easy to Transport & Store	Cost (\$)	Time to Complete Activity	Weight (lb)	Complexity of the System	
Weight Factor (W.F)	0.20	0.15	0.15	0.15	0.15	0.05	0.10	0.05	1.00
Screen Printer	5	5	5	5	5	5	4	5	4.9
3D Printer	5	3	5	5	5	5	5	4	4.65
Drill Press	5	5	3	3	4	4	4	3	4
Desktop CNC Router	4	5	5	3	2	3	3.5	2	3.65
Button Maker	3	5	5	2	3	4	3	2	3.45
Mini Injection Molding Machine	3	4	3	2	2	4	4	3	3

The screen printer received the highest overall rating (4.90) and was ultimately selected as the demonstration product. It met all major design and instructional criteria, offering:

- High visibility of process steps,
- Multiple opportunities for SMED modification,
- Relative ease of use and portability,
- Strong contrast between original and SMED workflows.

3.3. Project Final Plan

The final plan for implementing the SMED instructional lab involved a structured sequence to ensure meaningful student engagement and measurable outcomes. The lab activity consisted of three main phases:

1. Development of Lab Activity: Two T-shirt screen printing machines were prepared: one in its original traditional setup and one redesigned using SMED principles. Students also developed two different sets of work instructions, one intentionally vague and one clear and SMED-aligned, to highlight the impact of documentation quality on operational efficiency.
2. Hands-On Implementation: Students individually set up and operated both machines, following the respective work instructions. They recorded setup times, noted procedural differences, and provided subjective feedback on usability, clarity, and perceived difficulty. Observations were made regarding which steps caused confusion or delay.
3. Reflection and Analysis: After completing the tasks, students compared their experiences. Key factors such as setup time, physical effort, ease of use, and clarity of instructions were discussed. Students identified which SMED principles were applied and how they impacted the process. Structured reflection questions guided their analysis and reinforced lean manufacturing concepts.

4. Method

This study used a design-based research approach to evaluate how the redesign of a screen-printing system using SMED (Single-Minute Exchange of Dies) principles could reduce setup time and improve instructional clarity for undergraduate engineering students.

4.1. Redesign Of the Traditional Screen-Printing Process

The project began with a step-by-step analysis of a traditional t-shirt screen printing setup. The full process included 14 individual steps, ranging from manual placement of the t-shirt on the pallet to cleaning and drying tools after use. A baseline setup time was recorded at approximately 186 seconds (3.1 minutes). Each step was evaluated for potential modification according to SMED principles. Ten out of the fourteen steps were targeted for redesign. Common themes in the redesign as shown in Table 3 below included reducing manual alignment through the use of quick-alignment guides, replacing threaded knobs with toggle clamps, incorporating pre-aligned mounting systems, and minimizing unnecessary repositioning. Four steps were retained in their original form, typically because they were either already efficient or did not significantly impact setup time.

Table 3. Development of SMED

Step Description	Average time (Seconds)	Action
Place t-shirt on wood pallet	12	Update to SMED
Align t-shirt neck with pallet	9	Update to SMED
Mount screen on swinging hinge	21	Update to SMED
Lower hinge with screen in place	6	Keep original
Secure screen using black knobs	27	Update to SMED
Adjust screen alignment with shirt	15	Update to SMED
Adjust pallet position using 6 knobs	18	Update to SMED
Adjust shirt position if needed	6	Update to SMED
Apply ink above/below design	9	Update to SMED
Spread ink using squeegee (8 passes with force)	30	Update to SMED
Lift hinge after printing	6	Update to SMED
Remove printed t-shirt	6	Keep original
Clean screen and squeegee with cold water	14	Keep original
Dry tools after cleaning	7	Keep original
	186 seconds or 3.1 minutes	

4.2. Development of the SMED-Compatible Machine

The redesigned SMED machine integrated physical improvements to address key inefficiencies such as 1) Mechanical streamlining: Toggle clamps replaced screw-based locks, and spring-loaded hinges enabled smoother operation, 2) Visual and physical alignment: Pre-set guides and standardized component positions reduced the need for judgment-based alignment, 3) Tool-free adjustments: Quick-release mechanisms replaced knobs for positioning the pallet and screen. A process comparison table (Table 4) highlights the operational difference between the original and SMED versions of each step.

Table 4. Original Vs. SMED Process

Step Description	Original Machine Process	SMED Machine Process
Place t-shirt on wood pallet	Manual placement with visual alignment	Quick-alignment guides
Align t-shirt neck with pallet	Manual sliding, adjust for neck hole	Guided alignment marks; no adjustment needed
Mount screen on swinging hinge	Mounted while hinge is raised, screen faces up	Toggle clamps for quick placement; spring-loaded hinge
Lower hinge with screen in place	Manually lower hinge	Hinge lowers smoothly via assisted arm
Secure screen using black knobs	Tighten black knobs to secure screen	Toggle clamps replace black knobs for fast locking
Adjust screen alignment with shirt	Manual visual check, adjust knobs as needed	Pre-aligned screen mount with standardized stops
Adjust pallet position using 6 knobs	Loosen/tighten 6 knobs under pallet	Quick-release pins; no knobs to adjust
Adjust shirt position if needed	Manual repositioning	Minimal to no repositioning needed
Apply ink above/below design	Manually trail ink above/below design	Standard ink trays with positioning guides
Spread ink using squeegee (8 passes with force)	8 back-and-forth passes with force using squeegee	Single press using levered arm; consistent pressure
Lift hinge after printing	Manually lift hinge	Lift assisted with spring; ergonomic design
Remove printed t-shirt	Peel t-shirt off pallet	Peel t-shirt as before
Clean screen and squeegee with cold water	Rinse screen and squeegee under cold water	Same process
Dry tools after cleaning	Towel or air-dry tools	Same process

4.3. Time Study Analysis

Each process step in both the original and SMED machine was timed across multiple iterations. The SMED-modified process reduced the setup time from 186 seconds to approximately 98.8 seconds, a reduction of over 47%. This time savings was statistically validated using a paired t-test (see Section 5.1).

4.4. Integration Into the Instructional Lab

To reinforce student learning, both machines were integrated into a structured lab experiment. Students completed the same screen-printing task on each machine, using parallel sets of work instructions. Their setup times were recorded, and feedback was collected regarding usability, clarity, and process flow. Students also identified which machine better embodied lean principles such as reducing waste, simplifying setup, and separating internal from external setup steps.

5. Results and Discussion

The SMED-based redesign led to significant improvements in setup efficiency. Timing data collected from the original and modified machines show a reduction in total setup time from 186 seconds to 98.8 seconds, yielding a 47% decrease in total time. This reduction was validated with a

paired-sample t-test using data from 15 students, confirming the statistical significance of the improvement ($t = 43.65$, $p < 0.001$) as presented in table 5.

Table 5. Statistical Comparison

Metric	Original Setup	SMED Setup	Result
Average Setup Time (sec)	186	98.8	47% Decrease
Number of Observations (n)	15	15	
Standard Test Used	Paired t-test		
t-statistic			43.65
p-value			2.31×10^{-16}
Statistical Significance			Yes ($p < 0.01$)
Interpretation			Significant improvement

The most substantial improvements occurred in steps that were redesigned according to SMED principles. Notably, Secure screen using knobs instead of screws reduced time from 27 to 6 seconds, saving 21 seconds, spread ink using a press instead of a squeegee dropped the time from 30 to 10 seconds, and adjusting the pallet position using 6 knobs improved the time from 18 to 4.8 seconds. These time savings were visualized using a Pareto chart (see Figure 2), which clearly identifies the *vital few* steps responsible for the majority of the improvement.

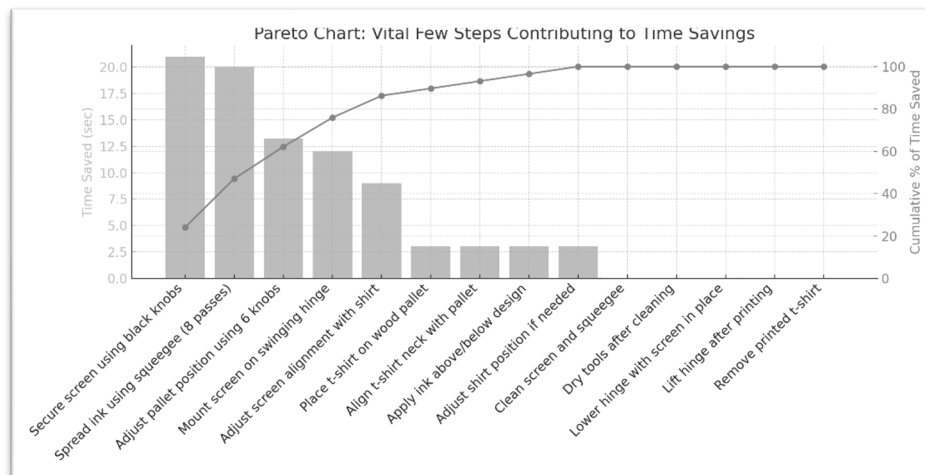


Figure 2. Pareto Chart for The T-Shirt Printing Improvements

5.1. Instructional Impact and Student Experience

Beyond time savings, qualitative feedback from students revealed strong support for the SMED-aligned setup. Students consistently preferred the redesigned machine for its simplicity, clarity of instructions, and physical ease of use. Students expressed that the clear and visually supported work instructions (developed on an 11×17 laminated poster) helped them follow the procedure

confidently and independently. In contrast, the original machine's vague list-format instructions were often cited as confusing and led to hesitation or errors. This distinction reinforced key lean learning outcomes, particularly the importance of standardized work and externalizing internal setup tasks. Figure 3 below show examples of the original machine work instruction and the SMED machine improved work instructions.

List Work Instructions for the Original Machine

1. Place the t-shirt with the top of the shirt at the top of the wood pallet and the bottom side of the shirt under the pallet.
2. Slide the t-shirt so that the neck hole has the smaller end of the wood pallet sticking out of the neck hole
3. Place the screen onto the swinging hinge with the flat part of the screen facing the t-shirt. The inside of the screen should be facing toward the ceiling. Place the screen onto the swinging hinge while it is raised.
4. Lower the swinging hinge with the screen in
5. Screw the black knobs clockwise to secure the screen
6. When pulling the screen down, see how the screen aligns with the shirt. If the screen does not align on the right place on the shirt, adjust the 6 black knobs that are beneath the pallet in order to adjust the placement of the pallet along the blue bar. If necessary, the position of the shirt can also be adjusted by moving the positioning of the shirt across the pallet.
7. Add a trail of ink right above or below the design on the screen
8. Take the squeegee and move the ink back and forth at least 8 times across the design. Be sure to apply a decent amount of force downwards to ensure that enough ink presses into the shirt]
9. Swing the hinge up.
10. Remove the t-shirt.
11. Be sure to dry the t-shirt in a hot dryer before ever placing it in the wash. Putting the t-shirt into the wash before ever drying it in hot air could cause the dye to come off in the wash and color the rest of your clothes in the wash.
12. Clean the screen and squeegee immediately after use with cold water.
13. Dry the screen and any other tools used.



Figure 3. Original and Improved Machine Work Instruction

5.2. Educational Value and Reflection

Student reflections underscored the hands-on nature of the lab as crucial to understanding SMED. Many reported that the exercise clarified the differences between internal and external setup steps in a way that lectures alone had not achieved. Observations also revealed that students began identifying waste-reduction opportunities on their own, suggesting a deeper engagement with lean principles. In addition, pairing technical setup with reflection questions enabled learners to translate physical improvements into conceptual understanding, bridging design thinking and process optimization.

5.3. Implications for Future Work

The positive outcomes from this pilot study suggest that hands-on SMED demonstration labs can serve as a highly effective educational strategy in lean manufacturing instruction. As a next step, the research team plans to develop a full Lean Lab with 10 interactive stations simulating production with a 1-minute takt time using Lego-based kits. Each station will introduce a lean concept (e.g., Kanban, 5S, continuous flow), allowing students to rotate through challenges in a gamified, time-sensitive environment. Future work will focus on publishing this lab model as a scalable framework that other institutions can readily adopt, demonstrating how low-cost, modular setups can transform lean manufacturing education and broaden student access to experiential learning in engineering curricula.

6. Conclusion

This project demonstrated the value of integrating lean manufacturing principles, specifically the Single-Minute Exchange of Dies (SMED), into undergraduate engineering education through a hands-on instructional lab. By redesigning a traditional screen-printing setup to embody SMED principles, the research team created a side-by-side comparison that not only improved process efficiency but also deepened student understanding of lean concepts. Quantitatively, the SMED-modified machine reduced setup time by approximately 47%, confirmed through a statistically significant time study. Qualitatively, students reported greater ease of use, increased confidence, and enhanced learning when working with the redesigned system and its visually guided instructions. The activity also helped students distinguish between internal and external setup tasks, a core tenet of SMED theory.

7. Acknowledgement

The authors gratefully acknowledge the contributions of WWU manufacturing students Brandon Groat, Kush Sharma, Nathan Van Dellen, and Ann Bercaw for their dedicated work on this project. We also thank the teams at Amjay and Wester Solutions for their valuable support.

8. Disclaimer Statements

Funding: None

Conflict of Interest: None

9. References

- Anand, G., & Kodali, R. (2008). Reduction in Setup Time by SMED: A Literature Review. *ResearchGate*. Retrieved from https://www.researchgate.net/profile/Girish-Naik/publication/290337295_Reduction_in_Setup_Time_By_SMED_A_Literature_Review
- Hornakova, N., & Jurik, M. (2020). SMED for Quick Changeovers in Foundry SMEs. *Acta Logistica*. Retrieved from https://www.actalogistica.eu/issues/2020/IV_2020_07_Jurik_Hornakova_Domcekova.pdf

- Jurik, M., Hornakova, N., & Domcekova, J. (2020). The Human-Centric SMED Approach. *Sustainability*. Retrieved from <https://www.mdpi.com/journal/sustainability>
- Khakpour, A., Ebrahimi, S., & Seyed-Hosseini, S. (2024). SMED 4.0: Single-Minute Exchange of Die with Industry 4.0. *Emerald Insight*. Retrieved from <https://www.emerald.com/insight/content/doi/10.1108/jmtm-08-2023-0333/full/pdf>
- Molla, A., et al. (2024). Application of SMED Techniques in Electronics Manufacturing. *Journal of Scientific Advances in Engineering Research*. Retrieved from https://www.researchgate.net/publication/380344135_SMED_Techniques_for_Rapid_Setup_Time_Reduction_in_Electronics_Industry
- Naik, G., & Chakravorty, S. (2015). Reduction in Setup Time by SMED: A Literature Review. *Emerald Insight*. Retrieved from <https://www.emerald.com/insight/content/doi/10.1108/SMED-Quick-Changeovers>
- Rafael, D., et al. (2023). Lean Manufacturing Using SMED and Value Stream Mapping. *ResearchGate*. Retrieved from https://www.researchgate.net/publication/367404800_Lean_Manufacturing_Approach_using_SME_D_Method_and_Value_Stream_Mapping_on_The_Spring_Beds_Production_Floor
- Shingo, S. (1985). *A Revolution in Manufacturing: The SMED System*. Productivity Press.
- Toki, I., et al. (2022). SMED in the Bangladeshi Garments Industry. *ResearchGate*. Retrieved from https://www.researchgate.net/publication/365894468_Single_Minute_Exchange_Die_SMED_A_sustainable_and_well-timed_approach_for_Bangladeshi_garments_industry

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INVESTIGATING CORROSION PROPERTIES OF ALUMINUM ALLOYS IN VARIOUS SALTWATER SOLUTIONS VIA ELECTROCHEMICAL ANALYSIS

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Abstract

Corrosion prevention of aluminum and its alloys is of great technological significance because of its expanding industrial applications such as aerospace, automotive, defense, energy, sports equipment, marine, and biomedical as a replacement for human body parts. This study aims to look at the corrosion properties of bare and Alclad 7075 T6 aluminum alloy in distilled water, 3%, and 5% saltwater solutions. The Gamry corrosion cell electrochemical device and a Potentiodynamic DC Corrosion test were utilized to study galvanic corrosion behavior. In the overall experiment, the bare 7075 T6 aluminum alloy demonstrated a higher corrosion rate than the Alclad 7075 T6 alloy in various concentrated saltwater conditions. The lowest corrosion rate was observed in distilled water solution for both bare and Al covered 7075 T6 alloys, while the highest corrosion rate at 5wt% saltwater.

Keywords: *Aluminum Alloys; Galvanic Corrosion; Potentiodynamic DC Corrosion Test.*

1. Introduction

Aluminum alloy is widely utilized in highway construction, railway cars, and airplanes due to its low density, strong machinability, corrosion resistance, and recyclability. However, it is susceptible to localized corrosion, such as pitting, intergranular, and exfoliation corrosion, which can cause structures to collapse in chloride-containing environments. The active components in aluminum alloys, such as magnesium and zinc, have negative standard reduction potentials and react with oxygen to generate passivating metal oxide layers. The most common cause of localized corrosion is damage to the passive surface coating.

Corrosion rate can vary bare and clad materials based on what types of cladding were used. Alclad products provide corrosion protection based on two key principles. Initially, the cladding material must be anodic in comparison to the base metal, giving cathodic protection in the event of significant

corrosion damage. Furthermore, the microstructure of the cladding material must have less intermetallic particles, resulting in higher localized corrosion resistance for the entire system, as demonstrated in various published scientific publications. Moreover, anodic coating or anodization can also improve the performance of corrosion resistivity even in various aggressive environments

Aluminum alloys vary greatly in mechanical strength and corrosion resistance based on their components and other conditions. Therefore, material selection should be based on the intended use environment. Rosliza et al. conducted electrochemical studies using AA6061 aluminum alloy at room temperature using tropical seawater. They found that sodium benzoate effectively inhibits corrosion of AA6061 in saltwater conditions.

This study investigates the corrosion behavior of bare and clad 7075-T6 aluminum alloys in various aqueous environments, including 3% and 5% saltwater solutions as well as distilled water. The novelty of this study lies in its comparative approach across multiple salinity levels, offering a more nuanced understanding of how environmental conditions influence corrosion dynamics in high-strength aluminum alloys. Additionally, anodic coating is applied to the bare alloy to evaluate its effectiveness in enhancing corrosion resistance. By integrating surface treatment analysis with environmental variability, this work provides valuable insights into material performance optimization for marine and industrial applications.

2. Experimental Procedure

In the present study, 7075 T6 bare aluminum and aluminum clad 7075 T6 alloy were selected, and the typical chemical specifications of the material are given in Table 1. The samples were cut to 50mm x 50mm size from a 1.6mm thick sheet. The surface was first cleansed with soap, then Alodine was used to eliminate any pollutants, and finally it was rinsed with distilled water for one minute and thoroughly dried. All assays were done with a Gamry corrosion cell kit. The Potentiodynamic DC corrosion analysis method was utilized to study corrosion behavior. The specimen was placed in a working electrode where the sample area is 4.89 cm², graphite was employed as a counter electrode, and Ag/AgCl, Hg/Hg₂SO₄ served as a reference electrode in the Gamry corrosion cell. Both alloys were tested using 3% saltwater, 5% saltwater, and distilled water solutions. Table 2 shows the Potentiodynamic test input parameters used in the test. The 7075 T6 bare alloy is known as B7075, while the Alclad 7075 alloy is known as AlCl7075. The experimental setup for the corrosion test is shown in detail in Figure 1 to measure the corrosion rate by generating Tafel Plot.

Table 1. Typical Material Chemical Specification Of 7075 T6 Alloy

Alloy	Al	Cr	Cu	Fe	Mg	Si	Zn	Others
7075 T6 Alloy	90%	0.18-0.28%	1.2– 2.0%	0.5% max	2.1 -2.9 %	0.4% max	5.1 - 6.1%	0.15%

Table 2. Potentiodynamic Test Input Parameters for Gamry Corrosion Measurement Cell

Al Alloy	Scan Rate(mV/s)	Initial voltage (V)	Final voltage (V)
B7075	0.638	-3.45	-3.70
AlCl7075	5.00	-3.44	-3.75

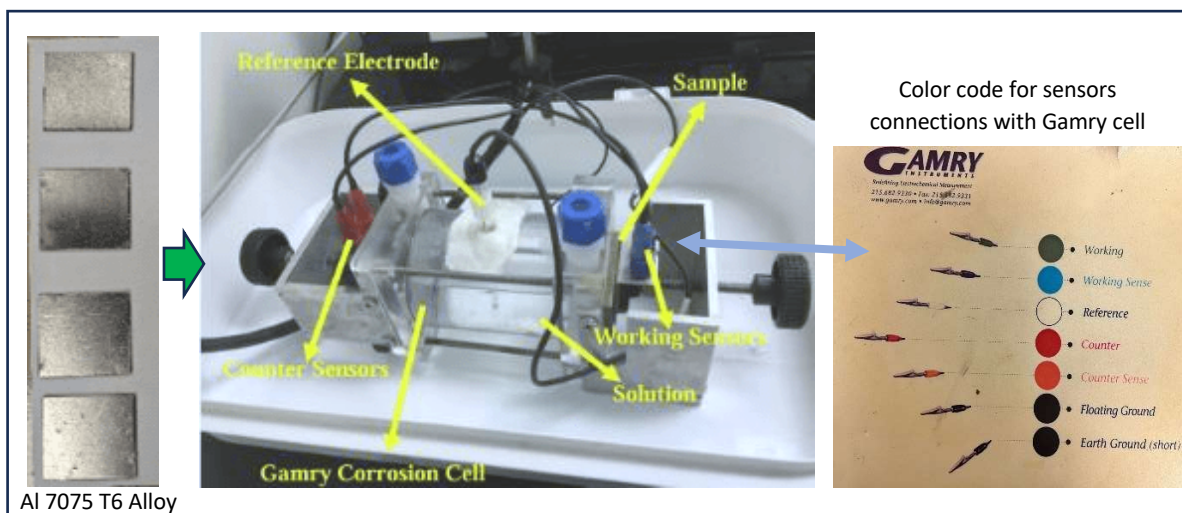


Figure 1. Corrosion Parameter Measurement Experimental Setup by Using Gamry Cell

3. Results and Discussion

3.1. Electrochemical Corrosion Measurement Analysis

Electrochemical corrosion measurement is an important approach for determining the rate and mechanism of corrosion in materials. Key approaches include Polarization Resistance (R_p), Electrochemical Impedance Spectroscopy (EIS), Tafel Extrapolation (Tafel slopes), and Electrochemical Frequency Modulation. These approaches provide information on electrochemical processes at the interface, charge transfer resistance, double-layer capacitance, and corrosion current density, which aids in the calculation of corrosion rate.

3.1.1. Potentiodynamic Polarization System

The Potentiodynamic polarization method is the most used corrosion analysis system among all polarization measuring techniques. The process includes multiple methods, such as cyclic polarization, linear polarization resistance, Potentiodynamic measurements, and Tafel extrapolation. Tafel extrapolation is one of the most used polarization methods, and it is a faster experimental methodology than the standard weight loss procedure. The Tafel extrapolation results are the focused area of discussion in this study due to its usefulness in corrosion investigations.

3.1.2. Tafel Extrapolation Method

Tafel is a Potentiodynamic test that relies on electrochemical kinetics. Using the mixed

potential theory of corrosion studies, the Tafel plot can help to forecast corrosion rate and potential. In this procedure, all the reactions occur on the surface of the specimen in contact with an aqueous electrolyte. All reactions in this method occur on the specimen's surface in contact with an aqueous electrolyte. The Tafel plot can be divided into two parts: first, the oxidation process on an anodic branch and second, the reduction reaction on a cathodic branch at E_{corr} . The slope of the anodic branch (shown in Figure 2) is known as the anodic Tafel constant (β_a), while the slope of the cathodic branch is known as the cathodic Tafel constant (β_c). If both tangent lines intercept at point (a), The distance between the origin to point (a) to the X axes is the value of i_{corr} , and the distance between the origin to point (a) to the Y axes represents the E_{corr} . The corrosion rate can be calculated either by software-generated or manual adjustment. To find out the software-generated corrosion rate (CR), it is necessary to select the anodic and cathodic regions and then choose the Tafel fit on Gamry farmwork. The software will automatically show the corrosion rate value. Another way is to manually draw the tangent line to both anodic and cathodic regions, find the intercept point, and it will give the E_{corr} and i_{corr} values. The below equations (1), and (2) can be used to calculate the corrosion rate.

$$CPR(\mu\text{m/y}) = 3.27 M i_{\text{corr}} / n\rho \dots\dots\dots(1)$$

$$CPR(\text{mpy}) = 0.129 M i_{\text{corr}} / n\rho \dots\dots\dots(2)$$

Here,

CPR = corrosion penetration rate

MPY = mills per year

M = atomic weight (g/mol)

ρ = density (g/cm³)

n = valence of the metal ion

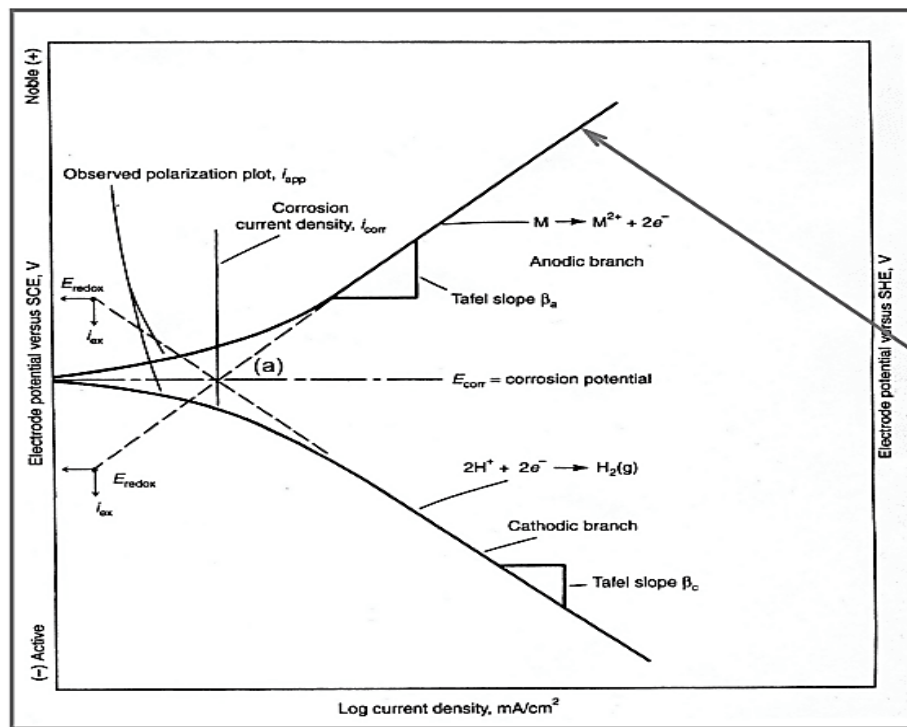


Figure 2. Graphical Representation of Tafel Plot Extrapolation with Electrochemical Corrosion Parameters

3.2. Corrosion Results of Bare and Clad Al Alloys

3.2.1. Corrosion Behavior of Bare 7075 T6 Alloys

The Potentiodynamic DC corrosion test result of the B7075 specimens in various solutions is shown in Table 3, which are obtained from the Tafel plots stacking for all samples shown in Figure 3. These Tafel plots are used to determine the corrosion current density and to find linear regions on both the anodic and cathodic sides of the plot. This technique gives the corrosion rate a numerical value, which is crucial for figuring out how long a material will last in a particular setting. According to Table 3, the corrosion rate is higher at 5% saltwater solution, but the rate decreased as the NaCl concentration in a saltwater solution was reduced to 3%. The B7075 T6 alloy has the best corrosion resistance performance, with a corrosion rate of 0.05 MPY in distilled water due to no presence of salt to enhance the corrosion. In a 3% saltwater solution, the corrosion rate increased to 0.23 MPY, but the specimen corroded at an earlier voltage and a faster corrosion rate of 0.394 MPY was observed in a 5% saltwater solution.

Table 3. Corrosion Test Result of B7075 With the E_{corr} and I_{corr} Values in Various Solutions

Specimen	Average E _{corr} (V)	Average I _{corr} (μA)	Average CR (mpy)	Standard Deviation (mpy)
B7075_5% Salt Water (SW)	2.72	4.57	0.394	0.02
B7075_3% Salt Water (SW)	2.76	2.6	0.23	0.01
B7075_Distilled Water (DTW)	2.85	0.42	0.05	0.004

Figure 4 depicts a comparison to better understand the change in corrosion characteristics. According to the chart, the corrosion rate potential gradually increased with the increased concentration of NaCl present in the saltwater electrolyte. Ions in saltwater, such as chloride and sodium ions, have the potential to be highly aggressive against aluminum surfaces. Aluminum oxide, a chalky, white coating, and pitting are both possible outcomes when the metal encounters saltwater waves. However, in lower concentrated saltwater solutions, the corrosion rate decreased significantly, and it is reduced further in distilled water solutions because distilled water is virtually impurity-free and has a neutral pH. Aluminum can be rejuvenated and relaxed by hanging out with distilled water, much like it would be at a spa. When aluminum corrodes in pure water, aluminum oxide, a thin protective layer, forms. By acting as a shield, this layer stops additional corrosion. Therefore, bare Al 7075 T6 Al alloy corrosion behavior is greatly influenced by the kind of water it comes into contact with and saltwater has a higher risk of corrosion compared to lower risk of corrosion in distilled water.

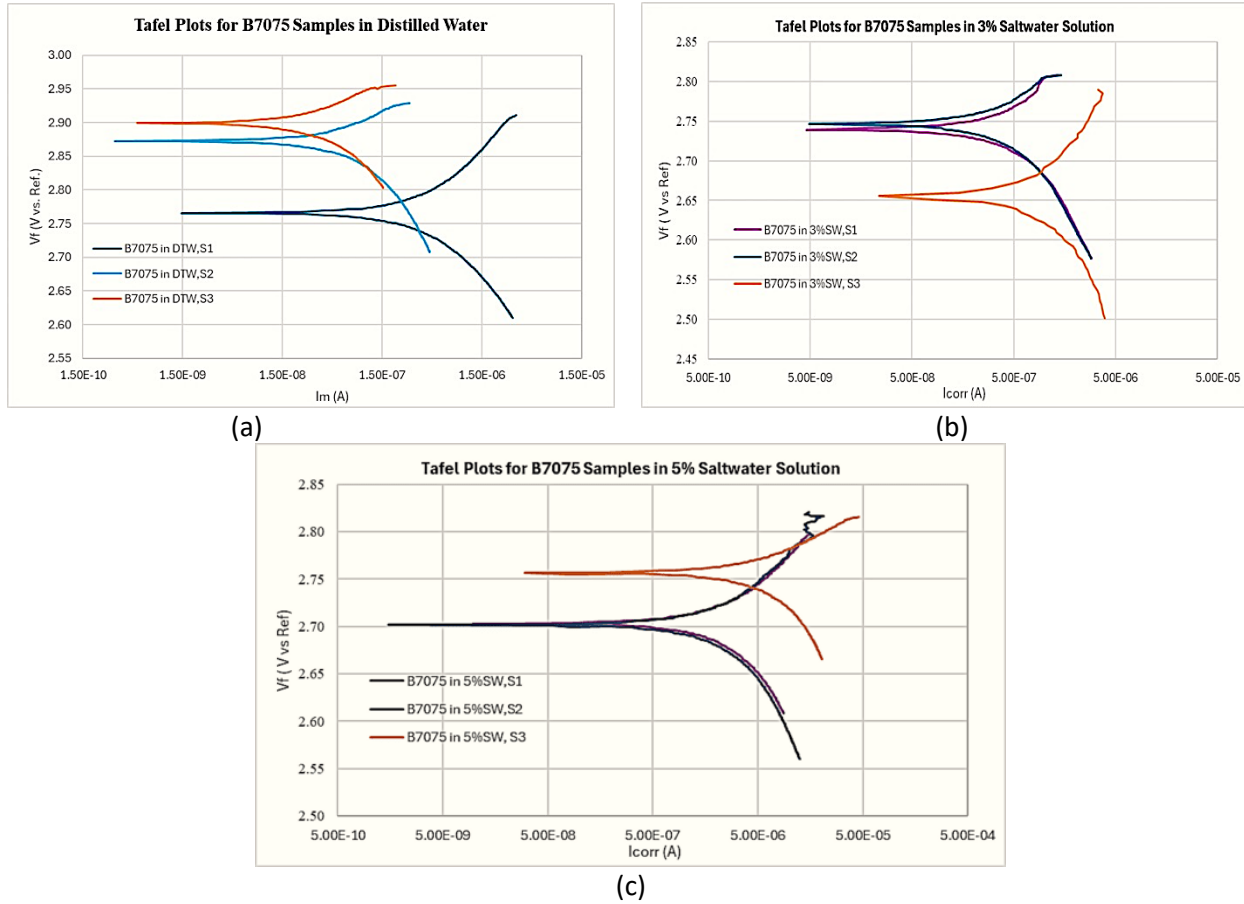


Figure 3. Tafel Plots for B7075 T6 Al Alloy in (A) DTW (B) 3% SW and (C) 5% SW Solutions

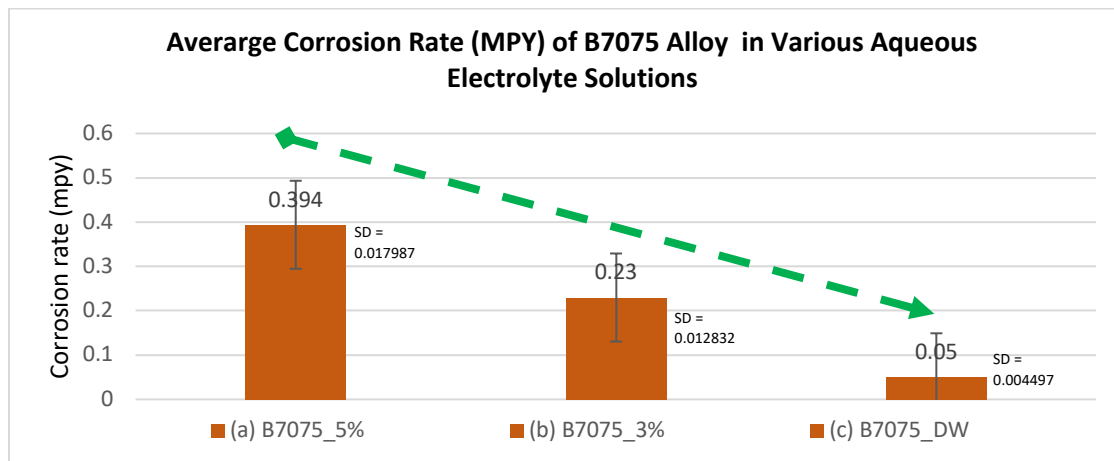


Figure 4. Corrosion Rate Comparison of B7075 T6 Alloy In 5%, 3%, Saltwater and DTW Water

3.2.2. Corrosion Behavior of Al Clad 7075 T6 Alloys

Figure 5 shows a graphical representation of the Potentiodynamic DC corrosion test (Tafel Plot) result for the AlCl7075 specimens, and Table 4 summarizes the average potential (E_{corr}), current density (I_{corr}), and corrosion rate (CR) which are obtained by using the software-generated Tafel fit. Based on the findings, the aluminum clad 7075 T6 alloy has a corrosion rate of 0.067 MPY in 5% salt water, 0.037 MPY in 3% salt water and the lowest corrosion rate of 0.005 MPY in distilled water due to the absence of salt and neutral pH value. However, the clad Al alloy samples exhibit better performance in terms of corrosion resistance and lifetime expectancy of the materials compared to bare Al 7075 alloy. Zinc and magnesium elements with the cladding of aluminum improve the alloy's capacity to tolerate extreme situations, such as exposure to sea water.

Table 4. Corrosion Test Result of AlCl7075 with The E_{corr} and I_{corr} Values in Various Solutions

Specimen	Average E_{corr} (V)	Average I_{corr} (μ A)	Average CR (mpy)	Standard Deviation (mpy)
AlCl7075_5% Salt Water (SW)	2.67	0.76	0.067	0.004
AlCl7075_3% Salt Water (SW)	2.70	0.43	0.037	0.01
AlCl7075_Distilled Water (DTW)	2.80	0.066	0.005	0.0004

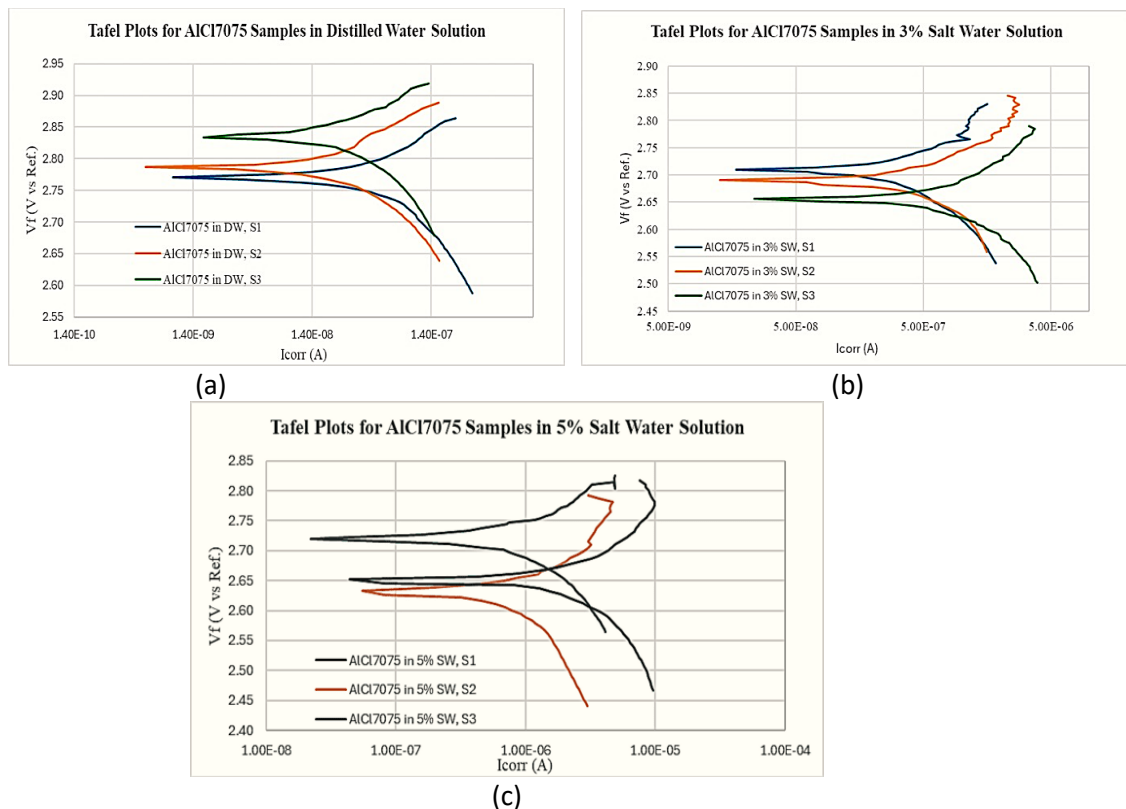


Figure 5. Tafel Plots for AlCl7075 Alloy in (A) DTW (B) 3% SW and (C) 5% SW Solutions

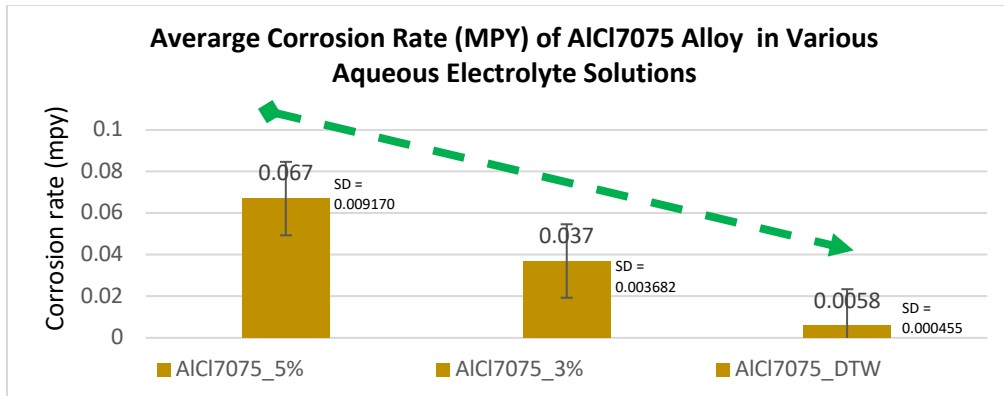


Figure 6. Corrosion Rate Comparison of AlCl7075 Alloy in 5%, 3% Saltwater, and DTW Water

Figure 6 illustrates the change in corrosion properties of AlCl 7075 alloy across different solutions. The graph indicates that the corrosion rate increases as the NaCl concentration in the saltwater electrolyte increases. Like bare 7075 T6 alloy, the NaCl contacted the surface and created a chloride layer, although the reaction was substantially slower for clad aluminum in all three corrosion settings due to the materials' cladding characteristics for clad Al 7075 alloy.

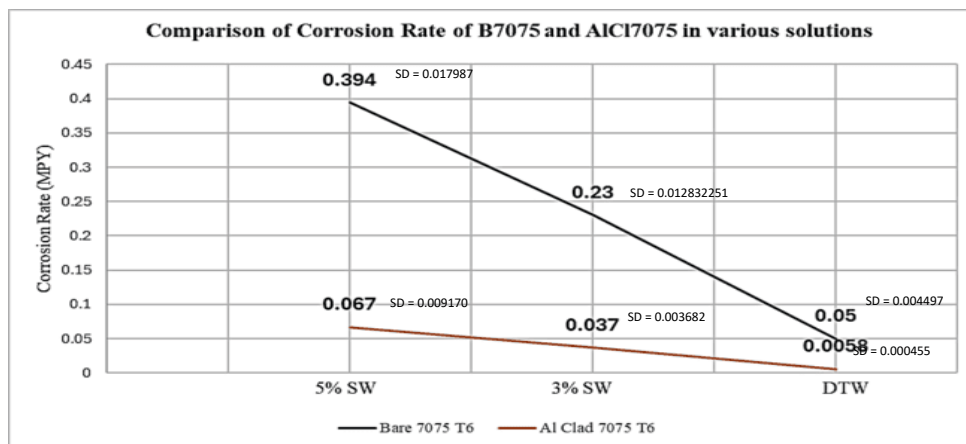


Figure 7. Average Corrosion Rate Comparison Between B7075 and Al-Clad 7075 T6 Aluminum Alloy

Finally, Figure 7 shows the performance of both bare and clad Al alloys under different environmental circumstances, demonstrating the substantial differences in corrosion resistance. The bare alloy has a substantially steeper slope, indicating that anions may easily pierce its surface, causing significant damage due to corrosion. Notably, aluminum's corrosion resistance rises as metal purity increases. It was observed that the inclusion of a pure aluminum cladding on the 7075 T6 alloy improves its corrosion resistance, resulting in corrosion rates of 0.067 MPY, 0.037 MPY and 0.0058 MPY when exposed to 5% salt water, 3% saltwater and distilled water, respectively. In comparison, the bare alloy performs significantly worse, with corrosion rates ranging from 0.394 MPY, 0.23MPY, 0.05 MPY under the identical circumstances.

4. Conclusions

The corrosion behavior of bare 7075 T6 alloy and Al-clad 7075 T6 aluminum alloy was investigated in a variety of saltwater and distilled water conditions. According to the findings of the preceding experiment, chloride and sodium ions have a significant influence on corrosion behavior. Both alloys are significantly impacted by the ions and exhibit substantial corrosion losses in 5% salt water; however, the impact of salt water on aluminum cladding 7075 was decreased when compared to the bare 7075 T6 alloy. Furthermore, a cladding of pure aluminum and presence of zinc and magnesium helped Al-clad 7075 alloy for the increased corrosion resistance performance compared to bare Al 7075 alloy in any harsh environment and enhanced the lifetime of the clad alloy significantly.

5. Acknowledgments

The authors greatly acknowledge Wichita State University and Turkish Aerospace Industries – USA (TAI-USA) for the technical support of the present study.

6. Disclaimer Statements

Funding: Wichita State University and Turkish Aerospace Industries – USA (TAI – USA)

Conflict of Interest: None

7. References

- Georgantzia E, Gkantou M, Kamaris GS (2021) Aluminium alloys as structural material: A review of research. *Eng Struct* 227:111372. <https://doi.org/https://doi.org/10.1016/j.engstruct.2020.111372>
- Li S, Yue X, Li Q, et al (2023) Development and applications of aluminum alloys for aerospace industry. *Journal of Materials Research and Technology* 27:944–983. <https://doi.org/https://doi.org/10.1016/j.jmrt.2023.09.274>
- Đuriška L, Černičková I, Priputen P, Palcut M (2021) Aqueous corrosion of aluminum-transition metal alloys composed of structurally complex phases: A review. *Materials* 14:5418
- Natishan PM, O'grady WE (2014) Chloride ion interactions with oxide-covered aluminum leading to pitting corrosion: a review. *J Electrochem Soc* 161:C421
- Xu W, Liu J, Zhu H (2010) Pitting corrosion of friction stir welded aluminum alloy thick plate in alkaline chloride solution. *Electrochim Acta* 55:2918–2923. <https://doi.org/https://doi.org/10.1016/j.electacta.2009.12.083>
- Wang J, Xiong F, Liu H, et al (2019) Study of the corrosion behavior of *Aspergillus niger* on 7075-T6 aluminum alloy in a high salinity environment. *Bioelectrochemistry* 129:10–17. <https://doi.org/https://doi.org/10.1016/j.bioelechem.2019.04.020>
- Petroyiannis P V, Pantelakis SpG, Haidemenopoulos GN (2005) Protective role of local Al cladding against corrosion damage and hydrogen embrittlement of 2024 aluminum alloy specimens. *Theoretical and Applied Fracture Mechanics* 44:70–81. <https://doi.org/https://doi.org/10.1016/j.tafmec.2005.05.006>
- Campestrini P, Terryn H, Hovestad A, de Wit JHW (2004) Formation of a cerium-based conversion coating on AA2024: relationship with the microstructure. *Surf Coat Technol* 176:365–381. [https://doi.org/https://doi.org/10.1016/S0257-8972\(03\)00743-6](https://doi.org/https://doi.org/10.1016/S0257-8972(03)00743-6)
- García-Rubio M, de Lara MP, Ocón P, et al (2009) Effect of posttreatment on the corrosion behaviour of tartaric-sulphuric anodic films. *Electrochim Acta* 54:4789–4800. <https://doi.org/https://doi.org/10.1016/j.electacta.2009.03.083>
- Li Y, Zhang P, Bai P, et al (2018) Microstructure and properties of Ti/TiBCN coating on 7075 aluminum alloy by laser cladding. *Surf Coat Technol* 334:142–149
- Tunc I, Karahan BD, Keles O (2020) A study on the corrosion behavior of 7072/3004/7072 clad aluminum alloy in different media. *J Mater Eng Perform* 29:4506–4514

- Usta A, Murad MdS, Asmatulu R, Ceylan M (2022) STUDYING THE ELECTROCHEMICAL BEHAVIORS OF ANODIZED METALLIC IMPLANTS FOR IMPROVED CORROSION RESISTANCE. *İstanbul Ticaret Üniversitesi Fen Bilimleri Dergisi* 21:117–135. <https://doi.org/10.55071/ticaretfbd.1109393>
- HB S, WB WN (2017) Electrochemical performances and corrosion inhibition of AA6061 in tropical seawater. *ASEAN Journal on Science and Technology for Development* 25:251–259
- Ohtsuka T, Nishikata A, Sakairi M, Fushimi K (2018) Electrochemical Measurement of Wet Corrosion. In: Ohtsuka T, Nishikata A, Sakairi M, Fushimi K (eds) *Electrochemistry for Corrosion Fundamentals*. Springer Singapore, Singapore, pp 17–39
- Xia D-H, Deng C-M, Macdonald D, et al (2022) Electrochemical measurements used for assessment of corrosion and protection of metallic materials in the field: A critical review. *J Mater Sci Technol* 112:151–183
- Aslam R (2023) Chapter 2 - Potentiodynamic polarization methods for corrosion measurement. In: Aslam J, Verma C, Mustansar Hussain C (eds) *Electrochemical and Analytical Techniques for Sustainable Corrosion Monitoring*. Elsevier, pp 25–37
- Atrens A, Song G-L, Shi Z, et al (2018) Understanding the Corrosion of Mg and Mg Alloys. In: Wandelt K (ed) *Encyclopedia of Interfacial Chemistry*. Elsevier, Oxford, pp 515–534
- Mol A (2016) *Active Protective Coatings: New-Generation Coatings for Metals*
- Flitt HJ, Schweinsberg DP (2005) Evaluation of corrosion rate from polarisation curves not exhibiting a Tafel region. *Corros Sci* 47:3034–3052. <https://doi.org/https://doi.org/10.1016/j.corsci.2005.06.014>

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HIGHER EDUCATION STUDENT SUCCESS: A SYSTEM TO EVALUATE DEGREE COMPLETION

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Abstract

Higher education institutions must cultivate a technically skilled workforce to meet increasing job demands. However, graduation rates remain low, with 40% of first-year students not completing their degrees. This research proposes an integrated system using machine learning, particularly neural networks, to predict student success based on multifaceted interactions. The model demonstrates a systematic approach to improving degree completion outcomes.

Keywords: *Neural Networks; Machine Learning; Prediction; Higher Education.*

1. Introduction

Higher education goals have evolved alongside technological advancements and shifts in workforce demands. During the mid-20th century, reforms increased enrollment and expanded access across socioeconomic groups (Bailey, 2017). However, a new challenge emerged as enrollment grew: low student completion rates (Rosenbaum et al., 2007). Research identified a growing workforce gap as industries required greater technical skills, yet the supply of prepared graduates remained insufficient (Governor's Business Council, 2002).

Efforts to improve retention and graduation rates have a long history in educational research. Tinto (1975, 1999, 2010) emphasized student persistence through institutional commitment, academic goals, and career aspirations—dimensions that continue to frame current approaches. Despite decades of research and intervention programs, completion rates remain concerning. The National Student Clearinghouse Research Center (Shapiro et al., 2018) reports that only 65.7% of four-year institutions graduate within six years, with community college rates substantially lower at 39.2%. Alarming, 40% of first-year college students will not graduate (Kirp, 2019), and only 17% of community college entrants transfer and complete a four-year degree within six years (Jenkins & Fink, 2015).

Historically, many initiatives have targeted specific student segments, such as minority, low-income, or first-generation college students (Alkhasawneh & Hargraves, 2014; Márquez-Vera et al.,

2016). While valuable, these segmented approaches have achieved limited system-wide improvements (Baran & Kihç, 2015). Increasingly, experts call for a more holistic view of student success that emphasizes helping all students define and achieve their educational goals while preparing for sustainable careers (Hiles, 2017; Kruger et al., 2017).

To support this shift, three critical elements are essential: fostering a culture of student success, leveraging information technology (IT) for predictive analytics, and ensuring that reforms are scalable and adaptable across institutions (Bailey et al., 2005; Grajek, 2017). Machine learning techniques, particularly neural networks, offer promising tools to model student interactions with institutional systems and predict degree completion outcomes.

The primary objective of this research is to develop an integrated system that models the complex interactions affecting student success and applies machine learning to predict degree completion. By creating a scalable and evidence-based framework, this work aims to inform strategic interventions and close the persistent gap between student enrollment and graduation.

2. Higher Education System to Evaluate Student Success

Understanding and predicting student success requires viewing the educational experience as a dynamic system of interacting factors. Representing this system through machine learning enables institutions to identify patterns, manage decision-making, and develop targeted strategies for improving degree completion (Birta & Arbez, 2013; Wasson, 2019).

This study proposes a system-based framework that models a student's journey through higher education, accounting for both pre-entry characteristics and institutional interactions. The system integrates a culture of student success, evidence-based IT support, and a focus on scalability to support predictive modeling across different institutions.

2.1 System Description

The system models student success as degree completion within 150% of the standard program time, aligning with the 1990 Student Right-to-Know Act (Alban & Mauricio, 2019). Inputs include students' pre-college characteristics, institutional interactions, and behavioral developments during enrollment. Outputs are categorized as either successful completion or non-completion of a degree program.

The structure identifies factors influencing student success, organizes them systematically, and supports the development of predictive models using machine learning techniques.

2.2 Methodology

A structured literature review identified key factors influencing student completion (Alban & Mauricio, 2019; Kuh et al., 2006; Cardona et al., 2020). These factors informed the system's architecture. A neural network model was then developed to validate the system structure by predicting student success outcomes.

2.3 Factors

Key factors impacting student success were grouped into six categories, as shown in Table 1.

Table 1. Categories Of Factors That Impact Student Success

Category		Description	Example Factors
1	Secondary school	Pre-college academic performance and readiness	High school GPA, standardized test scores, first-generation status
2	Socioeconomic	Demographic and financial background	Economic status, parental education level
3	Institutional	Institutional offerings and engagement	Instructor quality, course design, student support services
4	Financial aid	Financial support available to students	Scholarships, loans, emergency funding
5	Student behavior	Academic and personal habits during enrollment	GPA, LMS usage, study habits, student engagement
6	Transfer	Transfer process characteristics	Credits transferred, GPA at transfer, reasons for transfer

This categorization allowed a comprehensive but manageable structure for system modeling and predictive analysis.

2.4 System Structure

The proposed system architecture (Figure 1) integrates student inputs, institutional processes, and outcomes. External factors (secondary school and socioeconomic) define student readiness at entry, while internal factors (institutional, financial aid, behavior, and transfer) evolve throughout the academic experience.

The IT infrastructure operates as a transversal element, supporting synchronized data collection, integration across platforms, and predictive modeling capabilities.

Policies such as admission and graduation requirements (Table 2) guide the system's operations and influence student progression.

Table 2. Example Of System Rules

Category	Policy/rule
Admission requirements	Minimum grade point average (GPA)
	Minimum score for the standard entry test
	Minimum financial resources to cover at least a year of studies (e.g., tuition, boarding, alimentation, and university fees)
Completion requirements	Range of credits allowed to take in a semester (min-max)
	Minimum number of credits to graduate
	Classes required for graduation

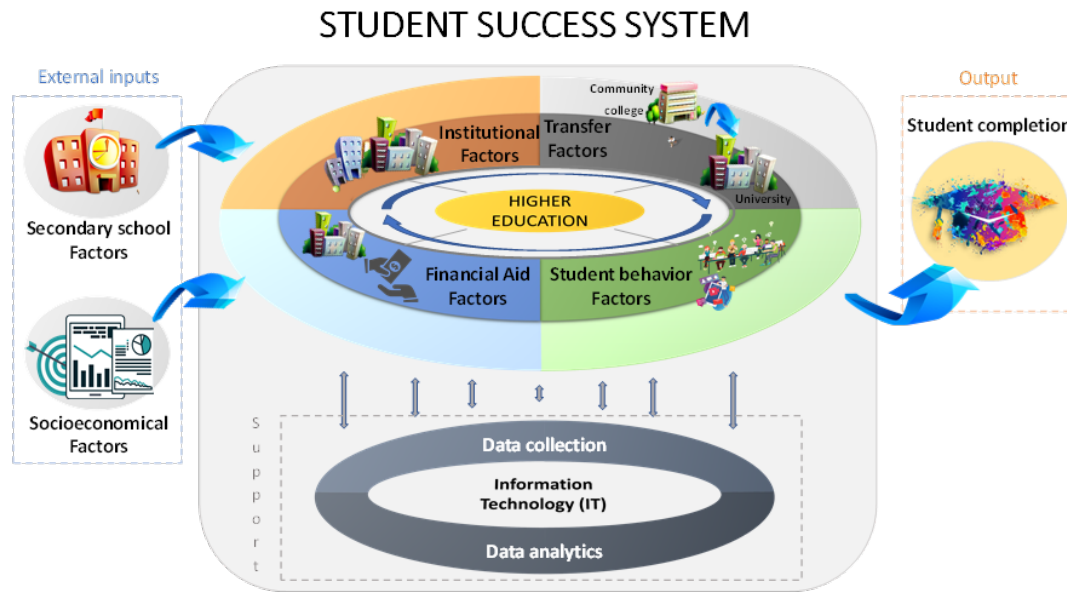


Figure 1. Higher Education Architecture for The Prediction of Student Success

2.5 Summary of External and Internal Factors

External factors or system inputs are usually collected during the student's admission process, and most will not change throughout the student's journey. For the prediction model, these factors are considered static. Two important categories of external inputs are secondary school factors and socioeconomic factors.

Secondary school factors include both academic attainment and college readiness. Academic attainment reflects a student's performance before entering higher education, such as scores on standardized entrance exams, high school GPA, and recognition through performance awards. College readiness extends beyond grades and test scores to include social integration, motivation to learn, participation in outreach activities, and involvement in pre-college intervention programs. Additionally, whether the student is the first generation in their family to attend college and their initial preference for a major are important elements of readiness.

Socioeconomic factors describe the demographic and financial background students bring to higher education. Demographic aspects include age, gender, economic status, and marital status. Family and peer support also play a role, as students' access to financial resources, encouragement from parents, and their parents' educational attainment can influence persistence and success.

Internal interaction factors are more dynamic and evolve as students engage with their institutions. These factors contribute to a holistic view of student success and are grouped into four primary categories: institutional, financial aid, student behavior, and transfer-related elements.

Institutional factors encompass several dimensions of the academic environment. Teaching quality is influenced by the instructor's experience, professional development, pedagogical preparation, workload, and employment status (e.g., adjunct, full-time, part-time, graduate teaching or research assistant). Pathway design refers to the structure and delivery of core courses, curriculum content, orientation practices, and class sizes. Peer involvement reflects opportunities for orientation programs and the availability of faculty who provide intentional academic advice and

mentoring. Campus environment factors include institutional policies, specific student support services outside academics (such as counseling and financial literacy), and broader commitments such as promoting a culture of diversity.

Financial aid factors capture the range of resources that support students financially. These include scholarships, grants, waiver programs, and awards. In addition, students may rely on loans or emergency support such as food pantries and short-term funding opportunities.

Student behavior factors describe the academic and personal habits that develop during enrollment. Academic attainment captures measures such as GPA, credit load, full- or part-time status, time to graduation, progression through study years, and instances of failed courses. Academic interaction includes the extent and quality of engagement with institutional systems like the learning management system (e.g., login frequency and duration) and involvement in campus activities or organizations. Academic preparation reflects how students approach studying, including habits, study hours, timing before tests, study modality (on-campus or distance), preferred study locations, and attendance. Student engagement measures motivation, satisfaction with the institution, willingness to re-enroll, and perceptions of institutional quality. Personal development includes self-awareness, social competence, ethical self-perception, and disciplinary history. Health habits, such as alcohol consumption and pre-existing health conditions, also contribute to overall student behavior.

Transfer factors capture the circumstances of students who move between institutions. Academic attainment in this context includes GPA, accumulated credits, and failed courses. Student goals are also central, particularly the reasons for transferring and the degree to which the new institution aligns with the student's aspirations and needs.

Finally, information technology support underpins the overall system by managing infrastructure for data collection and analysis. IT enables synchronization of multiple sources of student data, such as learning management system logs, ID card swipes, and emerging modalities like VR experiences. These data streams form the foundation for predictive modeling. It is important to note, however, that improving IT structures to support a student success system raises ethical challenges, which must be addressed carefully but are beyond the scope of this study.

3. Model Validation

A prediction model was developed using neural network (NN) techniques to evaluate the effectiveness of the proposed system architecture. Neural networks are widely recognized for their superior performance in student success prediction compared to machine learning methods such as decision trees and support vector machines (Delen, 2010; Dissanayake et al., 2016; Adejo & Connolly, 2018).

3.1 Validation Methodology

To validate the proposed architecture, a trial model for the classification of students was prepared using the NN technique. Factors from different categories in the system were selected according to the availability of information to create the dataset. Finally, the model was assessed using performance measures such as overall classification accuracy, precision, and recall.

NN was selected for this study, as it is currently the most widely used machine learning technique for predicting student success. Also, NN has shown better performance in the classification of student success in comparison with support vector machines and decision trees (Delen, 2010; Delen, 2011; Dissanayake et al., 2016; Babić, 2017; Raju & Schumacker, 2015; Adejo & Connolly, 2018).

3.2 Data

Public information for a bachelor's degree from a university in the Midwest was selected. Statistical reports and published studies of the institution in fall 2017 were used to create a database of 10,000 entries. The rules or interactions within the factors were defined based on institutional policies. The factors in secondary school, student behavior, and financial aid categories were characterized by the six categories established for the proposed system. Detailed information about the variables selected for the model, such as admissions requirements, student behavior, and financial aid, is presented in Tables 3 through 5, respectively.

Table 3. Rules To Define Admission Requirements Data

Factor	Rules
ACT score	Mean 28, Standard deviation (STD) 1.73
High school GPA	Mean 3.56, STD 0.4183
Class rank	Mean 79, STD 19.2

Table 4. Rules To Define Student Behavior Data

Factor	Rules
Self-identified as having been dishonest	No 81%
	Yes 19%
Self-perceived ethicalness	Range 1 (not at all) to 7 (excellent)
	Mean 5.6, STD 1.2
The student belongs to a Greek fraternity/sorority	No 78%
	Yes 22%
Overall GPA	-Average GPA is 3.52, STD 0.28 -Minimum GPA for graduation is 2.0 -Minimum GPA for transfer is 2.25 -Minimum GPA for financial aid is 1.67
Degree completion	4 years 33%
	6 years 24.6%
	8 years 11.4%
	Transfer 25%
	Drop out 5%
	More than 8 years, 1%

Table 5. Rules To Define Financial Aid Data

Factor	Rules
Received financial aid	Yes, need-based, 27%
	Yes, non-need-based, 22%
	No, 51%

The target variable was completion with two classes: completer (finished in 150% time to completion) was identified by the number 1, and non-completer (did not finish in 150% time to completion) was identified by the number 0. In preparing the dataset, the completion variable was defined as a multi-categorical variable (categories presented in Table 10) to specify students who would drop out or are still enrolled. In this manner, policies for financial aid and overall GPA could be modeled. Once financial aid and GPA variables were created, the target variable was converted to binary by defining completers (less than or equal to six years) and non-completers.

Once the dataset was created, a classification model for completion (target variable) was developed by applying the NN technique. STATISTICA 12 software was used in the implementation of the NN. The software uses an automated search that runs several networks with different combinations of initial parameters (e.g., training algorithm, number of hidden layers, error measure, and activation functions). Next, it retrieves the combinations with the highest classification accuracy. The model verification was performed using 10-fold cross-validation. The model was assessed based on the confusion matrices' results and the resulting networks' overall accuracy. The initial parameters of the networks are presented in Table 6.

Table 6. NN Initial Parameters

Parameter	Multilayer Perceptron (MLP)	Radial Basis Function
Hidden units (min-max)	4-12	21-30
Activation and output functions	Exponential, hyperbolic tangent, logistic, identity, sin	
Error functions	Sum of squares (SOS), entropy	
Number of networks generated	100	
Weight decay hidden and output	0.001-0.005	

3.3 Model Results

Using the different combinations of the initial parameters, 100 networks were trained, tested, and verified. A summary of the best five performing models is presented in Table 7 and Figure 2.

Table 7. Results Of the Best-Performing Networks

Network ID	Training Algorithm	Hidden Layers	Training Performance	Testing Performance	Validation Performance	Training Cycles	Error Function	Hidden Activation Function	Output Activation Function
1	MLP	6	98.6769	99.0000	98.9500	65	Entropy	Sine	Softmax
2	MLP	8	98.9077	99.1333	99.0500	23	Entropy	Tanh	Softmax
3	MLP	7	99.0308	99.1333	98.8000	44	SOS	Tanh	Tanh
4	MLP	9	98.8769	98.6667	98.4500	15	SOS	Exponential	Tanh
5	MLP	9	98.5385	98.9333	98.4000	19	SOS	Tanh	Sine

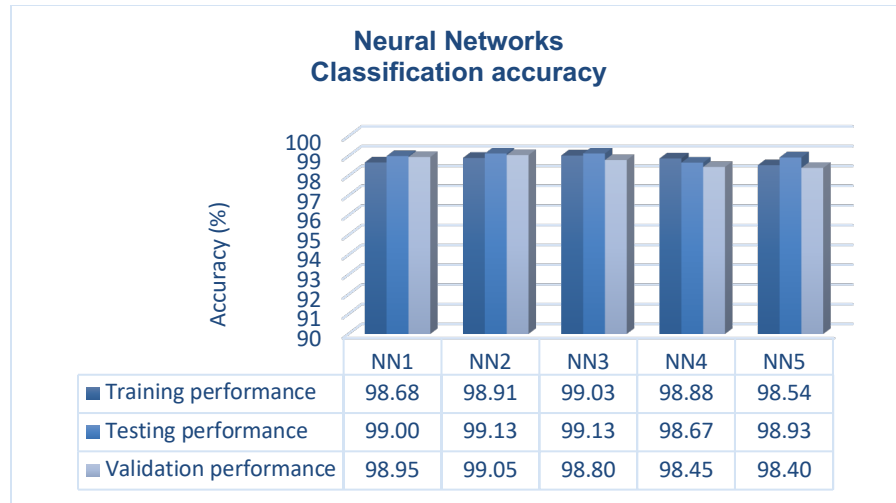


Figure 2. Training And Validation of Classification Performance

The results indicate high classification performance for the training, test, and validation sets. Further, the results indicate that every network is a good classifier of student success with relatively few misclassifications in each category (i.e., completer and non-completer). Also, the classification accuracy for the validation sets in all networks is not significantly lower than for the training set, which is a positive sign that the networks were not overfitted.

The overall classification accuracy for the validation set is higher for model 2; however, when analyzing the classification summaries for each network and their assessment measures of recall, specificity, precision, and negative predictive value (Table 8). Therefore, it was possible to conclude that network three has the most consistent prediction behavior for both the completer and non-completer classes.

Therefore, network three is the selected network for predicting student success using the specified variables to validate the architecture of the proposed system. Table 9 presents a summary of the network parameters.

The NN technique also allows for the identification of the impact of each variable in the model. It is calculated as a sensitive analysis of the error. STATISTICA 12 tests the sensitivity of the error when simulating changes in the variables used in the network (e.g., if an important variable is removed, the error will increase and vice versa). When the average error values from the different models are less than zero, the variable does not impact the model and can be removed.

As every NN has a different error, it is common to find slight changes in the order of impact of the variables for each model. Table 10 and Figure 3 present the results for the rank of the variables for each model, and the total rank is calculated as the average of all the results for each factor. ACT score, class rank, and self-perceived ethicalness are the most important predictors for this case. The analysis also indicates that all the variables chosen for the model have some impact on the prediction.

Table 8. Network Classification Summary

NN		Non-completer (0)	Completer (1)	All classes	Recall	Specificity	Precision	Negative Predicted Value
1	Total	4324	5676	10,000	0.987	0.989	0.985	0.990
	Correct	4267	5611	9878				
	Incorrect	57	65	1222				
	Correct (%)	98.68	98.85	98.78				
	Incorrect (%)	1.32	1.15	1.22				
2	Total	4324	5676	10000	0.994	0.986	0.982	0.995
	Correct	4298	5599	9897				
	Incorrect	26	77	103				
	Correct (%)	99.40	98.64	98.97				
	Incorrect (%)	0.60	1.36	1.03				
3	Total	4324	5676	10000	0.991	0.990	0.981	0.992
	Correct	4278	5622	9900				
	Incorrect	46	54	100				
	Correct (%)	98.94	99.05	99.00				
	Incorrect (%)	1.06	0.95	1.00				
4	Total	4324	5676	10000	0.976	0.985	0.991	0.993
	Correct	4284	5592	9876				
	Incorrect	40	84	124				
	Correct (%)	99.07	98.52	98.76				
	Incorrect (%)	0.93	1.48	1.24				
5	Total	4324	5676	10000	0.976	0.993	0.991	0.982
	Correct	4220	5637	9857				
	Incorrect	104	39	143				
	Correct (%)	97.59	99.31	98.57				
	Incorrect (%)	2.41	0.69	1.43				

Table 9. Network Parameters of The Best-Performing Network

Network ID	Training Algorithm	Hidden Layers	Training Performance	Testing Performance	Validation Performance	Training Cycles	Error Function	Hidden Activation Function	Output Activation Function
2	MLP	8	98.9077	99.1333	99.0500	23	Entropy	Tanh	Softmax

Table 10. Variable Rank from Global Sensitivity Analysis

FACTOR \ NN ID	NN 1	NN 2	NN 3	NN 4	NN 5	Average
ACT score	1.849	4.197	2.663	2.050	3.715	2.895
Class rank	1.105	1.202	1.669	0.986	1.146	1.221
Self-perceived ethicalness	1.015	1.100	1.045	1.017	1.029	1.041
High school GPA	1.029	1.078	1.045	0.941	1.030	1.025
Financial aid	0.999	1.021	1.002	0.998	1.000	1.004
Greek student	1.030	0.964	1.004	0.991	1.027	1.003
Dishonesty	1.000	1.000	1.000	1.000	1.000	1.000
GPA	1.000	0.990	0.998	1.000	0.994	0.996

Figure 3 shows the rank of each variable used to create the five different NN models. Several combinations of the initial parameters to run the model were tried to offer scientific validity, and the results presented the five best-performing models. The mechanics of the NN technique can identify the most important variables by completing the training period. As NN does not show the relationship between the variables because of the complex calculations within the iterations, a sensitivity analysis was performed to state the rank of importance of each variable in the model.

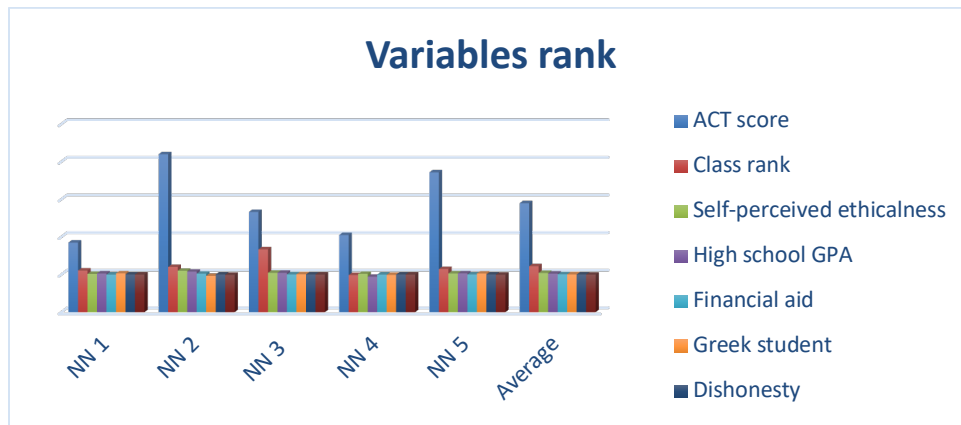


Figure 3. Variables Rank

The sensitivity analysis revealed that ACT score consistently emerged as the most influential predictor of student success across the five neural network models, with the highest average impact score among the variables tested. Class rank was also a strong contributor, reinforcing the importance of pre-college academic performance in predicting degree completion. In addition, self-perceived ethicalness and high school GPA demonstrated moderate but consistent influence, suggesting that both personal integrity and prior academic achievement play a role in persistence.

Other factors, such as financial aid status, Greek life participation, and overall GPA, showed relatively minor effects, with average importance values clustered close to 1.0. Notably, the variable dishonesty remained constant across all models with no variation, indicating it contributed little predictive power to the classification outcomes.

Together, these results highlight that a combination of standardized test scores, class standing, and personal attributes provides the strongest signals for predicting degree completion, while other

variables contribute marginally to the overall model performance.

Identifying the correlation of the variables within a model can give important information with respect to how one variable reacts to the other. Since the model only informs of a linear relationship between two variables, the analysis would be specific to the level of interaction of those two variables. This may be important when more details are needed after applying machine learning techniques.

The neural network validation demonstrated exceptionally strong predictive performance, with classification accuracies consistently above 98% across training, testing, and validation datasets. Notably, the results confirmed that network three offered the most stable and reliable classification of completers and non-completers, making it the preferred model for further analysis. The sensitivity analysis further highlighted ACT score, class rank, and self-perceived ethicalness as the most critical predictors of student success, supported by consistent contributions from high school GPA. These findings affirm the value of combining academic preparation and personal attributes in predictive models, while also demonstrating that neural networks can serve as a robust tool for identifying at-risk students and guiding institutional interventions.

4. Conclusions, Limitations, and Future Research

This study proposed a systematic framework for evaluating student success in higher education through an integrated set of factors and machine learning techniques. By modeling student characteristics and institutional interactions as a system, the approach enables evidence-based strategies to improve degree completion.

Using a neural network model validated with public data, the framework demonstrated strong predictive performance, achieving over 98% accuracy in identifying student completion outcomes. Key predictors included ACT scores, class rank, and self-perceived ethicalness, providing insights into the factors most critical to student success. The model affirms that when integrated with a comprehensive system architecture, machine learning can support institutional efforts to identify at-risk students and improve retention strategies.

Several limitations should be noted. The model was developed using public data from a single institution, which may limit generalizability. Additionally, available data restricted the range of factors in the model, suggesting that future studies could benefit from richer and more longitudinal datasets. Privacy and ethical considerations in data collection also require careful attention in practical implementation.

Future research should expand the system architecture to include more diverse institutional contexts and explore how dynamic factors, such as mid-program academic engagement, further influence student outcomes. Applying the model progressively and holistically across student populations can support scalable reforms and contribute to closing workforce gaps in technical fields.

Ultimately, institutions must align predictive analytics initiatives with transparent policies, ethical data practices, and a student-centered approach to achieve sustained improvements in completion rates.

5. Disclaimer Statements

Funding: None

Conflict of Interest: None

6. References

- Adejo, O. W., & Connolly, T. (2018). Predicting student academic performance using a multi-model heterogeneous ensemble approach. *Journal of Applied Research in Higher Education*, 10(1), 61-75.
- Alban, M., & Mauricio, D. (2019). Predicting university dropout through data mining: a systematic literature review. *Indian Journal of Science and Technology*, 12(4), 1-12. doi:[10.1108/JARHE-09-2017-0113](https://doi.org/10.1108/JARHE-09-2017-0113)
- Alkhasawneh, R., & Hargraves, R. H. (2014). Developing a hybrid model to predict student first-year retention in STEM disciplines using machine learning techniques. *Journal of STEM Education: Innovations and Research*, 15(3), 35-42. <https://www.jstem.org/jstem/index.php/JSTEM/article/view/1805>
- Babić, I. D. (2017). Machine learning methods in predicting the student academic motivation. *Croatian Operational Research Review*, 8, 443-461. doi:[10.17535/corr.2017.0028](https://doi.org/10.17535/corr.2017.0028)
- Bailey, T. (2017). Community colleges and student success: Models for comprehensive reform. *Educause Review*, 52(3), 33-42.
- Bailey, T., Jenkins, D., & Leinbach, T. (2005). Is student success labeled institutional failure? Student Goals and Graduation Rates in the Accountability Debate at Community Colleges. CCRC Working Paper No. 1. *Community College Research Center, Columbia University*.
- Baran, B., & Kihç, E. (2015). Applying the CHAID algorithm to analyze how achievement is influenced by university students' demographics, study habits, and technology familiarity. *Journal of Educational Technology & Society*, 18(2), 323-335.
- Birta, L. G., & Arbez, G. (2013). *Modelling and simulation*. London: Springer.
- Cardona, T., Cudney, E., & Snyder, J. (2019a). Predicting degree completion through data mining. Proceedings of the ASEE Annual Conference & Exposition, Tampa, FL. <https://ieeexplore.ieee.org/document/8257209>
- Cardona, T., Cudney, E., & Snyder, J. (2019b). Predicting student retention using artificial neural networks. Proceedings of the IISE Annual Conference, Orlando, FL.
- Cardona, T., Cudney, E., Snyder, J., & Hoerl, R. (2020). Predicting student degree completion using random forest. Proceedings of the ASEE Annual Conference & Exposition.
- Delen, D. (2010). A comparative analysis of machine learning techniques for student retention management. *Decision Support Systems*, 49(4), 498-506.
- Delen, D. (2011). Predicting student attrition with data mining methods. *Journal of College Student Retention: Research, Theory & Practice*, 13(1), 17-35. <https://doi.org/10.2190/CS.13.1.b>
- Dissanayake, H., Robinson, D., & Al-Azzam, O. (2016, January). Predictive Modeling for Student Retention at St. Cloud State University. In Proceedings of the International Conference on Data Mining (DMIN) (p. 215). The Steering Committee of the World Congress in Computer Science, Computer Engineering and Applied Computing (WorldComp).
- Governor's Business Council. (2002). *Building An Effective and Aligned P-16 Education System: What Should Higher Education Do to Enhance Student Access and Success?* ERIC Clearinghouse.
- Grajek, S. (2017). Top 10 IT Issues, 2017: Foundations for Student Success. *EDUCAUSE*, 52(1), 11-58.
- Handel, S. J. (2013). The transfer moment: The pivotal partnership between community colleges and four-year institutions in securing the nation's college completion agenda. *New Directions for Higher Education*, 2013(162), 5-15.
- Hiles, H. (2017). Student Success, Venture Capital, and a Diverse Workforce: An Interview with Heather Hiles. *Educause Review*, 52(3), 22-30.
- Hora, M. T., & Oleson, A. K. (2017). Examining study habits in undergraduate STEM courses from a situative perspective. *International Journal of STEM Education*, 4(1), 1-19. <https://doi.org/10.1186/s40594-017-0055-6>
- Iam-On, N., & Boongoen, T. (2017). Improved student dropout prediction in Thai University using ensemble of mixed-type data clusterings. *International Journal of Machine Learning and Cybernetics*, 8(2), 497-510. doi:[10.1007/s13042-015-0341-x](https://doi.org/10.1007/s13042-015-0341-x)
- Jenkins, D., & Fink, J. (2015). What we know about transfer. New York, NY: Columbia University, Teachers College, Community College Research Center.

- Kelly, A. P., & Schneider, M. (Eds.). (2012). *Getting to graduation: The completion agenda in higher education*. JHU Press.
- Kirp, D. (2019). The college dropout scandal. *The Chronicle Review*.
<https://www.chronicle.com/interactives/20190726-dropout-scandal>
- Klempin, S., & Karp, M. M. (2018). Leadership for transformative change: Lessons from technology-mediated reform in broad-access colleges. *The Journal of Higher Education*, 89(1), 81-105.
<https://doi.org/10.1080/00221546.2017.1341754>
- N. Kondo, M. Okubo and T. Hatanaka, "Early Detection of At-Risk Students Using Machine Learning Based on LMS Log Data," 2017 6th IIAI International Congress on Advanced Applied Informatics (IIAI-AAI), Hamamatsu, Japan, 2017, pp. 198-201, doi: [10.1109/IIAI-AAI.2017.51](https://doi.org/10.1109/IIAI-AAI.2017.51).
- Kruger, K., Martin, R., Mehaffy, G., & O'Brien, J. (2017). Student Success: Mission-Critical. *Educause Review*, 52(3), 11–20.
- Kuh, G. D., Kinzie, J. L., Buckley, J. A., Bridges, B. K., & Hayek, J. C. (2006). *What matters to student success: A review of the literature*, 8. Washington, DC: National Postsecondary Education Cooperative.
- Márquez-Vera, C., Cano, A., Romero, C., Noaman, A. Y. M., Mousa Fardoun, H., & Ventura, S. (2016). Early dropout prediction using data mining: a case study with high school students. *Expert Systems*, 33(1), 107-124. doi:[10.1111/exsy.12135](https://doi.org/10.1111/exsy.12135)
- Matthews, D. (2012). A Stronger Nation through Higher Education: How and Why Americans Must Achieve a Big Goal for College Attainment. A Special Report from Lumina Foundation. *Lumina Foundation for Education*.
- Melguizo, T., Kienzl, G. S., & Alfonso, M. (2011). Comparing the educational attainment of community college transfer students and four-year college rising juniors using propensity score matching methods. *The Journal of Higher Education*, 82(3), 265-291.
<https://doi.org/10.1080/00221546.2011.11777202>
- Raju, D., & Schumacker, R. (2015). Exploring student characteristics of retention that lead to graduation in higher education using data mining models. *Journal of College Student Retention: Research, Theory & Practice*, 16(4), 563–591.
- Restuccia, D., Taska, B., & Bittle, S. (2018). Different skills, different gaps: Measuring and closing the skills gap. https://www.burning-glass.com/wp-content/uploads/Skills_Gap_Different_Skills_Different_Gaps_FINAL.pdf.
- Rosenbaum, J. E., Deil-Amen, R., & Person, A. E. (2007). *After admission: From college access to college success*. Russell Sage Foundation.
- Shapiro, D., Dundar, A., Huie, F., Wakhungu, P. K., Bhimdiwala, A., & Wilson, S. E. (2018). Completing college: A national view of student completion rates – Fall 2012 cohort (Signature Report 16). Herndon, VA: National Student Clearinghouse Research Center.
- Thomas, L., Herbert, J., & Teras, M. (2014). A sense of belonging to enhance participation, success, and retention in online programs. *The International Journal of the First Year in Higher Education*, 5(2), 69–80. <https://doi.org/10.5204/intjfyhe.v5i2.233>
- Tinto, V. (1975). Dropout from higher education: A theoretical synthesis of recent research. *Review of Educational Research*, 45(1), 89–125. <https://doi.org/10.2307/1170024>
- Tinto, V. (1999). Taking retention seriously: Rethinking the first year of college. *NACADA Journal*, 19(2), 5-9. doi:[10.12930/0271-9517-19.2.5](https://doi.org/10.12930/0271-9517-19.2.5)
- Tinto, V. (2010). From theory to action: Exploring the institutional conditions for student retention. In *Higher Education: Handbook of Theory and Research* (pp. 51–89). Springer, Dordrecht. doi:[10.1007/978-90-481-8598-6_2](https://doi.org/10.1007/978-90-481-8598-6_2)
- Wasson, C. (2019, July). The State of Systems Engineering Technical Practice versus Discipline: A Survey of INCOSE Chapter Attendees in North America. In *INCOSE International Symposium* (Vol. 29, No. 1, pp. 591–619). doi:[10.1002/j.2334-5837.2019.00623.x](https://doi.org/10.1002/j.2334-5837.2019.00623.x)

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AIRCRAFT SPAR PRODUCTION: MATERIALS, METHODS, & PRODUCTION MANAGEMENT USING LINEAR PROGRAMMING

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Abstract

The design and manufacturing of aircraft wing spars are extremely important to aerospace manufacturing, particularly in enhancing manufacturing efficiency and sustainability. In the past, when creating spar production plans, engineers approached material selection and manufacturing process optimization as separate decisions, which often resulted in higher costs. This study presents a mixed-integer linear programming (MILP) framework that takes a more united approach to spar production. Several production case studies were developed using different material and process combinations. To support this analysis, data comparing dissimilar materials and their properties were compiled from existing literature. These case studies were assessed using the MILP framework to see how well they performed. The results show that an integrated approach to manufacturing can help engineers reduce waste, improve sustainability, and use materials more efficiently.

Keywords: *Mixed-Integer Linear Programming (MILP); Aerospace Manufacturing; Spar Production; Process Efficiency; Sustainable Manufacturing.*

1. Introduction

In the aerospace industry, the design and manufacture of spars, which are essential structural components of aircraft wings, has always required careful coordination, involving a balance of high performance, low weight, and cost efficiency. Optimizing this process requires selecting the right combination of materials and manufacturing methods. In the past, decisions about materials and manufacturing processes were made without the other in mind; materials were selected based on their performance, and processes were chosen based on feasibility or familiarity. This lack of coordination frequently resulted in unsatisfactory results, overlooking material behavior, and ineffective processes (Shercliff & Lovatt, 2001). It is only in recent years that the importance of an integrated approach has begun to be recognized, offering the possibility of more efficient and effective designs.

The purpose of this study is to analyze an integrated approach to manufacturing using Mixed-Integer Linear Programming (MILP). The paper specifically focuses on the application of MILP to spars. This method is particularly relevant to Industry 4.0 and provides data on the comparison of materials and their properties.

It is hypothesized that MILP can optimize the process of spar manufacturing in the aerospace industry by exploring the relationship between material selection and processing methods. To test this hypothesis, a MILP framework was constructed to optimize cost, time, and machine utilization.

Submitted: April 30, 2025

Revised: September 14, 2025

The model incorporated input parameters, including material properties, processing times, and machine availability, to assess trade-offs in production strategies. The results of this study suggest that MILP offers an efficient methodology for spar production. The optimization of cost and time, and utilization of machine engagement were achieved by creating a MILP framework. Constructed by drawing on materials properties, machining times, and machine availability found in literature, the model assessed the cost of various strategies, including the most dominant ones.

2. Literature Review

A critical aspect of spar design and manufacturing is the selection of appropriate materials based on mechanical properties, corrosion resistance, and processing requirements (Saravanan et al., 2023). As highlighted by Saravanan et al., this selection process involves balancing strength, stiffness, toughness, density, and creep resistance while also considering cost and manufacturability. For spars that must withstand heavy loads while remaining lightweight, these trade-offs are unavoidable. These challenges emphasize the need for systematic evaluation methods, such as MILP, to balance competing requirements in spar design. To further understand these trade-offs, the following sections discuss the material properties, manufacturing processes, and processing times most relevant to spar production.

2.1. Material Properties in Spar Manufacturing

Commonly used materials in the spar manufacturing process include aluminum alloys such as 7075-T6 and 2024-T4, titanium alloys like Ti-6Al-4V and Ti-5553, composite materials such as carbon fiber reinforced polymers (CFRP), and steel alloys like AISI 4130 and 4340.

With the development of cladding and anodizing processes (Visser et al., 2016), aluminum-based alloys emerged as the leading materials for aircraft construction. Aluminum alloys are widely favored for their high strength-to-weight ratios, cost-effectiveness, and good machinability (Soni et al., 2023). Additionally, titanium alloys provide exceptional strength, corrosion resistance, and natural durability, but come with significantly higher costs and lower machinability (Gawali et al., 2023). CFRP composites are valued for their ultralightweight properties, high specific stiffness, and versatility in forming complex structures. However, limitations such as high production costs, impact susceptibility, and environmental sensitivity affect their widespread use (Tolga & Costas, 2014). According to Visser et al. (2016), steel alloys offer high tensile strength, good fatigue resistance, and cost-efficiency but can add significant weight. Gathered from Soni et al. (2023), Visser et al. (2016), Gawali et al. (2023), and Tolga & Costas (2014), the key material properties have been compiled and summarized in Table 1.

2.2. Manufacturing Processes for Spar Materials

For aluminum alloys, CNC extrusion presses (Sheppard, 2013) and horizontal milling machines (Knap et al., 2024) are commonly used for efficient shaping and machining. Steel alloys like AISI 4130 and 4340 are processed using techniques such as horizontal milling (Knap et al., 2024), hydraulic forging, and precision grinding, which enhance their tensile strength and maintain tight tolerances. These often require additional treatments like galvanizing or chromate plating to improve corrosion resistance, which is typically less of a concern for other materials.

Titanium alloys are processed using high-precision methods like 5-axis CNC machining, hydraulic forging, and additive manufacturing (AM) to accommodate their exceptional strength and hardness (Motyka et al., 2019). Additive manufacturing requires longer processing times and specialized tools (Mosallanejad et al., 2023). CFRP components are typically fabricated through autoclave systems, composite lay-up techniques, and filament winding, enabling lightweight and high-strength

structures with minimal material waste (Chen et al., 2023). Additionally, Gawali et al. (2023) states that AM, while offering design freedom and material efficiency, is also increasingly applied to advanced aerospace parts for both titanium and composites, due to its ability to produce complex geometries efficiently. Factors such as these need to be taken into consideration when assessing and creating production strategies.

Table 1. Material Properties

Material	Specific Alloy	Strength-to-Weight Ratio <i>(matweb.com)</i>	Corrosion Resistance <i>(Lei et al., 2022; Visser et al., 2016; Sérgio et al., 2006; Katangur et al., 2006)</i>	Priming & Corrosion Protection <i>(Visser et al., 2016; Schweitzer, 1989; Barroqueiro et al., 2019)</i>
Aluminum	7075-T6	High (Yield: 503 MPa)	Moderate, susceptible to stress corrosion cracking	Anodizing, Chromated chemical conversion coatings, Wash primer
	2024-T4	High (Yield: 434 MPa)	Poor, prone to intergranular corrosion	Requires cladding (Alclad) and anodizing
Steel	AISI 4340, 17-4 PH SS	High to Very High (Yield: 470)	Moderate, Excellent corrosion resistance due to PH	Galvanizing, anodizing, minimal priming needed for stainless steel
	AISI 4130	High	Moderate to excellent (depending on alloy)	Galvanizing, chromate plating for steel
Titanium	Ti-6Al-4V	Very High (Yield: 880 MPa)	Excellent, Forms Natural oxide layer	No priming is required but can be anodized or coated.
	Ti-5553	Very High (Yield: 1000-1100MPa)	Excellent, corrosion-resistant	No priming needed, very high corrosion resistance
	Ti-3Al-2.5V	Very High	Excellent	No priming is needed, can anodize for additional protection.
Composite	Carbon Fiber (CFRP)	Very High	Excellent, non-corrosive	UV-resistant coating as needed

2.3. Processing time for spar materials

For the materials analyzed in this paper, the processing times vary from less than an hour to 12 hours. Gathered from Whalen et al. (2021) and other relevant sources, the estimated processing times and associated manufacturing methods are summarized in Table 2. Since longer processing times can increase overall production costs and reduce productivity, they are a key factor in material

and method selection. Among the methods, CNC extrusion press is the fastest (Whalen et al., 2021), while filament winding is among the slowest. Ideally, manufacturers seek processes that minimize processing time.

3. Methodology

The goal is to optimize the production of sheet/plate units (e.g., metal, or composite sheets/plates) using a set of machines and alloys. Using input from table 2, the model considers: cost minimization, production time minimization, and machine usage minimization. Conversely, the model is subject to constraints such as machine availability, alloy availability, and sheet/plate unit production requirements.

3.1. Sets, Indices and Parameters

First, two sets are defined: M , the set of machines, indexed by $m \in M$; and A , the set of alloys, indexed by $a \in A$. Next, parameters for describing cost, time, and resources are introduced. The cost of producing one spar sheet/plate unit using machine m and alloy a ($C_{m,a}$), the processing time (in hours) to produce one sheet/plate unit using machine m and alloy a ($T_{m,a}$), the available units of alloy a (U_a), and the availability (in hours) for machine m (Q_m).

Additionally, the production requirement denoted by (S) represents the total number of spar sheet/plate units required. Finally, a large constant (M) is defined for use in the machine-alloy usage constraint.

Next, the decision variables which represent quantities to be determined are defined. Specifically, two decision variables are introduced:

- $x_{m,a}$: This represents the number of sheet/plate units produced using machine m and alloy a . It is an integer value and must be a non-negative integer ($x_{m,a} \in Z_+$).
- $y_{m,a}$: This is a binary variable (0 or 1) that indicates whether machine m is used with alloy a in production ($y_{m,a} \in \{0, 1\}$).

Table 2. Material to Method Mapping with Cost and Processing Time

Machine	Material	Specific Alloy	Cost (\$/sheet or plate) <i>(mcmaster.com)</i>	Processing Time (hrs.) <i>(Whalen et al., 2021; Barroqueiro et al., 2019)</i>	Best Use Cases
CNC Extrusion Press: Extrusion	Aluminum	7075-T6	\$8.04-\$15.4	0.8-2	High-strength aircraft structures, including spars
		2024-T4	\$9.06-\$17	1.5-2.5	Light structures, moderate strength, fuselage
Horizontal Milling Machining	Aluminum, Steel	6061-T6, AISI 4340	\$5.58-\$12.9, \$8-\$9	3–7	General aerospace, high-load aircraft structures
5-Axis CNC Machining	Titanium	Ti-6Al-4V	\$20.0-\$30.0	10	High-stress applications, wing spars, engine mounts
	Titanium	Ti-5553	\$20.0-\$25.0	12	Ultra-high-strength aerospace parts
Hydraulic Forging Press	Steel, Titanium	AISI 4130, Ti-3Al-2.5V	\$7-9	7–8	High-load structures, tubular aircraft components
Autoclave System	Composite	Carbon Fiber (CFRP)	\$25.0-\$40.0	12.5	Ultralightweight aerospace component, complex geometries
Composite Lay-Up Table	Composite	Carbon Fiber (CFRP)	\$25.0-\$40.0	12.5	Lightweight, high-strength components <i>(Steinberg, 1986)</i>
Precision Grinder: Finishing	Steel	AISI 4340, 17-4 PH SS	\$4.84-\$9	6–7	High-tensile and fatigue-resistant aircraft components
3D-Metal Printer	Titanium	Ti-6Al-4V, Ti-5553	\$20.0-\$25.0	10–12	Complex high-strength aerospace parts
Filament Winding	Composite	Carbon Fiber	\$25.0-\$40.0	12.5	Curved and tubular aerospace structures

3.2. Objective Functions and Constraints

The model uses decision variables $x_{m,a}$ (units produced on machine m with alloy a) and $y_{m,a}$ (binary indicator if machine–alloy pair (m,a) is active). A full description of machines, alloys, cost and time parameters, and availability values used in the case study is provided in Section 3.3. Given cost parameters $C_{m,a}$, processing times $T_{m,a}$, machine capacities Q_m , alloy limits U_a , demand S , and large constant M , the objectives are:

- Minimize Total Costs: $\sum_{m \in M} \sum_{a \in A} [C_{m,a} * x_{m,a}]$
- Minimize Production Time: $\sum_{m \in M} \sum_{a \in A} [T_{m,a} * x_{m,a}]$
- Minimize Machine Usage : $\sum_{m \in M} \sum_{a \in A} [y_{m,a}]$

As mentioned earlier, four constraints keep the model realistic: machine capacity limits total hours per machine, alloy availability limits output to stock on hand, the production requirement ensures demand is met, and a big-M activation constraint controls production through an on/off decision for each machine–alloy pair, so no output occurs unless it's activated and fewer setups are used.

- Machine availability constraints: $\sum_{m \in M} \sum_{a \in A} [T_{m,a} * x_{m,a}] \leq Q_m \quad \forall m \in M$
- Alloy availability constraints: $\sum_{m \in M} x_{m,a} \leq U_a \quad \forall a \in A$
- Sheet /Plate production requirement: $\sum_{m \in M} \sum_{a \in A} [x_{m,a}] \geq S$
- Machine-alloy usage enforcement constraint: $x_{m,a} \leq M * y_{m,a} \quad \forall m \in M, \forall a \in A$

To summarize, the MILP model helps balance cost, time, and resources in producing spar sheets/plate. By selecting different objective functions, trade-offs between minimizing costs or time, maximizing output, or reducing machine usage can be explored.

3.3. Input Data

For a given set of machines, alloys, costs, processing times, and constraints, the model determines: how many spar sheet/plate units to produce with each machine-alloy combination, which machines to use, the total cost, time, and resource usage.

The following input data were used in our case study:

- **Machines:** CNC Extrusion Press, Horizontal Milling Machining, 5-Axis CNC Machining, Hydraulic Forging Press, Autoclave System, Composite Lay-Up Table, Precision Grinder, 3D-Metal Printer, and Filament Winding.
- **Alloys:** 7075-T6, 2024-T4, 6061-T6, AISI 4340, 17-4 PH SS, AISI 4130, Ti-6Al-4V, Ti-5553, Ti3Al-2.5V, Carbon Fiber (CFRP).
- **Cost Parameters** (C_m, a): The cost of producing one sheet/plate unit using each machine-alloy combination.
- **Time Parameters** (T_m, a): The processing time (in hours) to produce one sheet/plate unit using each machine-alloy combination.
- **Production Requirement** (S): 200 sheet/plate units (minimum).
- **Large Constant** (M): 1,000 (used in the machine-alloy usage constraint).
- **Alloy Availability** (U_a): The available units of each alloy are given below in Table 3.
- **Machine Availability** (Q_m): The maximum processing time (in hours) available for each machine is given below in Table 4.

Table 3. Available Units for Each Alloy/Material

Alloy/Material	Available Units
7075-T6	100
2024-T4	100
6061-T6	100
AISI 4340	100
17-4 PH SS	100
AISI 4130	100
Ti-6Al-4V	50
Ti-5553	50
Ti-3Al-2.5V	50

Table 4. Maximum Processing Time Quotas for Each Machine

Machine	Maximum Processing Time (Hours)
CNC Extrusion Press	200
Horizontal Milling Machining	400
5-Axis CNC Machining	300
Filament Winding	500
Hydraulic Forging Press	300
Autoclave System	500
Composite Lay-Up Table	500
Precision Grinder	300

4. Results

The MILP model was solved for three different objectives, and the results are summarized in Table 5 and Table 6. Table 5 gives an overview of the total production cost, the average processing time per unit (in machine hours), and the number of machines used. When the goal was to minimize cost, the solution came to \$2,209.60 with an average of 5.59 hours per unit, using four machines. When it was minimizing time, the cost increased slightly to \$2,662.30 but processing time reduced to 4.51 hours per unit using four machines. Minimizing machine usage costs \$2,440.00 with the same 4.51 hours per unit, again using four machines. Table 6 expands further, showing how units were assigned to each machine-alloy pair. The cost objective concentrates volume on low-cost pairs, the time objective shifts volume to faster pairs, and the machine-usage objective groups production on fewer pairs. Using more than four machines could lower cost or time if extra cheap or fast capacity is available, but without such capacity, big improvements are unlikely.

4.1. Summary Of Results

Table 5. Results Of the Milp Model

Objective	Total Cost	Time per sheet/Plate (Hours)	Total Machines Used
Minimize Total Cost	\$2,209.60	5.59	4
Minimize Production Time	\$2,662.30	4.51	4
Minimize Machine Usage	\$2,440.00	4.51	4

4.2. Detailed Breakdown

Table 6. Results Of the Milp Model Under Different Optimization Objectives

Objective	CNC Extrusion Press	Horizontal Milling	Hydraulic Forging Press	Precision Grinder
Minimize Total Cost	7075-T6: 64 units	AISI 4340: 57 units	Ti-3Al-2.5V: 37 units	17-4 PH SS: 42 units
Minimize Production Time	7075-T6: 100 units	6061-T6: 57 units	Ti-3Al-2.5V: 1 unit	17-4 PH SS: 42 units
Minimize Machine Usage	7075-T6: 100 units	AISI 4340: 57 units	AISI 4340: 1 unit	AISI 4340: 42 units

5. Discussion

Below is a detailed analysis of the findings, focusing on strategic implications and operational trade-offs:

5.1. Strategic Alignment of Objectives

The cost-minimization objective yields the lowest total cost (\$2,209.60) but extends production time to 1,117 hours, making it suitable for cost-sensitive scenarios. In contrast, prioritizing shorter production time reduces it to 901 hours, though at a higher cost of \$2,662.30, making it a better strategy for time-sensitive operations. Alternatively, minimizing machine usage strikes a balance, achieving a moderate cost (\$2,440.00) and production time (901 hours) while simplifying operational demands and reducing machine-related overhead. Although both methods have the same production time, the time-prioritization technique is more costly in comparison to the machine-minimization strategy. This suggests that prioritizing a budget while trying to maintain optimal production time makes the second strategy much more favorable.

5.2. Trade-Offs And Decision-Making

The model shows a clear trade-off between minimizing costs and reducing production time. Additionally, minimizing machine usage reduces operational complexity but limits production flexibility. These factors must be considered by managers regarding their organization's priorities.

Across all objectives, a diverse range of alloys and machines are utilized throughout. Furthermore, the use of carbon fiber (CFRP) signifies the potential for the use of advanced materials in production, leading to new market opportunities but requires careful consideration of cost and time implications.

5.3. Scalability And Future Planning

The model's flexibility allows it to scale with changing production requirements, where increasing budgets or machine availability can enable higher production volumes or the use of more advanced materials. Managers can also use the model to perform scenario analysis, such as evaluating the impact of budget cuts, machine downtime, or changes in alloy availability, ensuring resilience in production planning.

6. Conclusion

This study demonstrates the effectiveness of MILP in optimizing spar production through an integrated evaluation of materials, methods, and machine allocation. The results show trade-offs among cost, time, and machine utilization, while also illustrating how an integrated approach can enhance sustainability and efficiency when including advanced materials such as CFRP and titanium alloys. Future work could extend this model by considering environmental impacts, allowing machine downtime uncertainty, and scaling to

larger production systems.

7. Disclaimer Statements

Funding: None

Conflict of Interest: None

8. References

- Bao, L., Li, K., Zheng, J., Zhang, Y., Zhan, K., Yang, Z., Zhao, B., & Ji, V. (2022). Surface characteristics and stress corrosion behavior of AA 7075-T6 aluminum alloys after different shot peening processes. *Surface and Coatings Technology*, 440, 128481. <https://doi.org/10.1016/j.surfcoat.2022.128481>
- Barroqueiro, B., Andrade-Campos, A., Valente, R. A. F., & Neto, V. (2019). Metal Additive Manufacturing Cycle in Aerospace Industry: A Comprehensive Review. *Journal of Manufacturing and Materials Processing*, 3(3), 52. <https://doi.org/10.3390/jmmp3030052>
- Dursun, T., & Soutis, C. (2014). Recent developments in advanced aircraft aluminium alloys. *Materials & Design (1980-2015)*, 56, 862–871. <https://doi.org/10.1016/j.matdes.2013.12.002>
- Gawali, S. K., Pandey, G. C., Bajpai, A., & Jain, P. K. (2022). Large-part manufacturing using CNC-assisted material extrusion-based additive manufacturing: issues and challenges. *International Journal on Interactive Design and Manufacturing (IJIDeM)*, 17(3), 1185–1197. <https://doi.org/10.1007/s12008-022-01097-4>
- Katangur, P., Patra, P. K., & Warner, S. B. (2006). Nanostructured ultraviolet resistant polymer coatings. *Polymer Degradation and Stability*, 91(10), 2437–2442. <https://doi.org/10.1016/j.polymdegradstab.2006.03.018>
- Knap, A., Dvořáčková, Š., & Váňa, M. (2024). Creation of an Aluminum Alloy Template with a Surface Structure by Micro-Milling for Subsequent Replication of the Microstructure to Achieve Hydrophobicity. *Journal of Manufacturing and Materials Processing*, 8(1), 26. <https://doi.org/10.3390/jmmp8010026>
- Mohammad Hossein Mosallanejad, Abdi, A., Farshid Karpasand, Nassiri, N., Iuliano, L., & Abdollah Saboori. (2023). Additive Manufacturing of Titanium Alloys: Processability, Properties, and Applications. *Advanced Engineering Materials*, 25(24). <https://doi.org/10.1002/adem.202301122>
- Motyka, M., Ziaja, W., & Sieniawski, J. (Eds.). (2019). *Titanium Alloys: Novel Aspects of Their Manufacturing and Processing*. BoD—Books on Demand.
- Saravanan, V., Ramachandran, M., Sivaji, C., & Rajkumar, S. (2023). Analysis of Materials Used in Spar of Human Powered Aircraft by TOPSIS Method. *Aeronaut. Aerosp. Eng.*, 1, 19-27.
- Schweitzer, P. A. (1989). *Corrosion and Corrosion Protection Handbook*. (2025). Google Books. <https://books.google.com/books?hl=en&lr=&id=l4kmb8QHkooC&oi=fnd&pg=PR3&dq=Schweitzer>
- Sheppard, T. (1999). Extrusion of aluminium alloys. In *Springer eBooks*. <https://doi.org/10.1007/978-1-4757-3001-2>
- Shercliff, H. R., & Lovatt, A. M. (2001). Selection of manufacturing processes in design and the role of process modelling. *Progress in Materials Science*, 46(3-4), 429–459. [https://doi.org/10.1016/s0079-6425\(00\)00013-x](https://doi.org/10.1016/s0079-6425(00)00013-x)
- Soni, R., Verma, R., Kumar Garg, R., & Sharma, V. (2023). A critical review of recent advances in aerospace materials. *Materials Today: Proceedings*. <https://doi.org/10.1016/j.matpr.2023.08.108>
- Steinberg, M. A. (1986). Materials for Aerospace. *Scientific American*, 255(4), 66–73. JSTOR. <https://doi.org/10.2307/24976058>
- Visser, P., Terryn, H., & Mol, J. M. C. (2016). Aerospace Coatings. *Active Protective Coatings*, 315–372. https://doi.org/10.1007/978-94-017-7540-3_12
- Whalen, S., Olszta, M. J., Md. Reza-E-Rabby, Roosendaal, T. J., Wang, T., Herling, D. R., Brandon Scott Taysom, Suffield, S., & Overman, N. (2021). High speed manufacturing of aluminum alloy 7075 tubing by Shear Assisted Processing and Extrusion (SHAPE). *Journal of Manufacturing Processes*, 71, 699–710. <https://doi.org/10.1016/j.jmapro.2021.10.003>

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REDUCING OCCUPATIONAL HAZARDS IN MANUFACTURING THROUGH ADDITIVE MANUFACTURING: A SAFETY CENTRIC APPROACH

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Abstract

Additive Manufacturing (AM) is a novel field that has revolutionary advantages when compared with traditional reductive manufacturing processes, specifically in terms of safety in the workplace. The more AM technologies are integrated into manufacturing and industrial applications; the greater the value of understanding the safety implications will be. Research indicates that AM reduces mechanical, chemical, thermal and physical risks, which reduces the occurrence of injuries. AM control systems are largely digitized, reducing the probability of human error and reducing material waste. This paper examines the role of AM in reducing manufacturing hazards while comparing it with traditional manufacturing practices, while reviewing case studies, limitations and the future of manufacturing with AM and its adoption in Industry 4.0.

Keywords: *Additive Manufacturing; Manufacturing Safety; Industry 4.0; Workplace.*

1. Introduction

In 2023 8,943 severe injury reports were submitted to the Occupational Safety and Health Administration (OSHA), worldwide it is estimated that 2.3 million laborers lost their lives from occupational accidents every year as noted by Hämäläinen Päivi et al. (2007). Some of the most common “Events and Exposures” reported to OSHA were classified as “Caught in running equipment or machinery during regular operation” and “Caught in running equipment or machinery during maintenance, cleaning” making up over 10% of all OSHA reports in 2023. These cases primarily stem from traditional styles of manufacturing, partially due to the commonality of traditional methodologies but also due to the nature of reductive manufacturing. Additive manufacturing in juxtaposition is devoid of many common occupational hazards commonly found in traditional manufacturing.

(Gibson, Rosen, & Stucker, 2021) Additive Manufacturing (AM) is defined as the process of creating three-dimensional objects by adding material layer by layer based on a digital model. Traditional manufacturing techniques can be reduced to two fields, reductive manufacturing and casting. Reductive manufacturing is nearly the opposite of additive manufacturing, where a prefabricated material is taken, and material is removed to create the desired form. Casting is an application where molten material is poured into a mold in order to create the desired product. Both fields of traditional manufacturing have tendencies toward different occupational hazards. This paper will compare traditional manufacturing techniques with AM with a focus on the safety and the prevalence of occupational risks.

2. Occupational Hazards of Traditional Manufacturing

Traditional manufacturing is far more common when compared to AM. By starting with the manufacturing industry in its modern state, a baseline for safety can be established. Occupational injuries

data in manufacturing and all sectors of the economy will be utilized as a benchmark for safety; The U.S. Bureau of Labor Statistics (BLS) records incidence rates of occupational injuries and illnesses. Comparing the statistics provided, occupational risks of all sectors versus manufacturing can be determined. “Incidence rate of nonfatal occupational injuries and illnesses by case type, manufacturing, private industry, 2016-2020” (Bureau of Labor Statistics, 2020). shows a “rate of 2.7 per 100 full-time workers” across all sectors; compared to a rate of 3.1 in the manufacturing sector. This comparison indicates that manufacturing occupations tend to have (nearly 15%) more occupational incidents than other fields. For this reason, safety in manufacturing has been of significant concern.



Figure 1. Injury Report Rate by Year

The concerns in manufacturing have been noted in other studies. Lai et al. (2022) noted, regarding safety in the U.S. manufacturing sector that “...there has been a remarkable workplace safety improvement lacking a satisfactory explanation.”. The graph provided in Figure 1 demonstrates an injury and illness rate decrease of over 60% in the manufacturing sector from 1991-2011. The rate of accidents and the interest in remedying these issues is an important aspect of understanding the continuous challenge the manufacturing sector faces, and how emerging technologies will be able to improve upon this trend.

Different methodologies used in manufacturing create unique occupational hazards, as AM has yet to be widely adopted studies of contemporary occupational hazards should be used to determine where safety may be improved. Berhan, et al. (2020) surveyed 446 employees at various companies classified as part of the “Iron, Steel and Metal Manufacturing Industries” compiling injuries workers received from their occupation. The survey gave categories of injuries/incidents for the workers to report any incidents they may have experienced. The most common “Accidents or Injuries” found during Berhan’s study were fractures and dislocations, followed closely by abrasions, burns, and piercings. The commonality of each category is a beneficial fact when considering additional information.

OSHA tracks the nature of each severe injury report made. Examining reports from 2015 through April 2024 in the NAICS (North American Industry Classification System) 333517 classification, the origins of manufacturing-related injuries are recorded. “Caught in running equipment or machinery during maintenance, cleaning”, and other machinery related origins made up the top “Events and Exposures”.

When organized by body parts, fingertips and fingers made up over 60% of injury locations. These statistics provide insights into the types of injuries that are likely to occur in the manufacturing sector.

Acknowledging current machining methodologies are a significant source of injuries, several government organizations have created guidelines for machine operations. The NIOSH (National Institute for Occupational Safety and Health) has developed a generalized safety protocol. NIOSH recommends that employers “Safeguard any machine part, function, or process that might cause injury when possible.”, educate employees on machine safety, and follow specific regulations set by local governments and insurance providers. In addition to employer practices NIOSH also notes worker practices: adherence to safety guidelines, staying up to date on safety training, and being attentive whilst using machinery. The implementation of policies is a mitigative solution, whereas a change of manufacturing methodologies may be a more effective way to reduce occupational hazards.

3. The Role of Additive Manufacturing in Enhancing Safety

In manufacturing AM is used for rapid prototyping, producing complex designs while reducing production time and cost for small batches of parts. Instead of developing individual assembly lines or custom machinery to create necessary products with small batch sizes, AM opens the possibility of a sole device for all the manufacturing needs. AM possesses several attributes that traditional manufacturing lacks, a key attribute being safety; with material, environmental, and user related safety being major improvements when compared to traditional counterparts.

3.1 Practicality & Waste Reduction

There are several benefits besides safety to consider with AM. One such benefit of using AM is design flexibility, with direct extrusion methods allowing the creation of complex geometry. AM allows lightweight complex forms without sacrificing strength, improving safety especially in the aerospace industry by enhancing fuel efficiency. Customization without large-scale production is another benefit of AM, specifically in the medical sector. Where AM can produce custom implants, prosthetics, and casts for bone fractures custom-designed for specific patients without requiring complex manufacturing processes. Printing parts as a single piece reduces the number of joints and potential failure points, enhancing product reliability and safety.

Economically, AM reduces the waste of materials by eliminating the need to remove non-desired material as traditional reductive manufacturing practices require. In which most of the removed material is required to be recycled or wasted. As reported by Khalid and Peng (2021), it is reported that AM can reduce the materials used in final parts by 35-80%. Lighter components made with AM can reduce the total weight of devices and lead to a reduced energy consumption rate. Since plastic and powder-based AM technology are readily available and can do a variety of things on the same device it can reduce the cost of shipping and usage of shipping methods by producing as many components as possible locally. It was additionally noted that reduced shipping equates to less usage of transportation methods and thus less emissions. “Manufacturing activities are responsible for 19% of the world’s greenhouse gas emissions and 31% of the United States’s total energy usage”.

3.2 Safer Work Environment Due to AM

“Traditional manufacturing often requires complex manual adjustments, introducing the risk of human error. In contrast, the automated execution of additive manufacturing minimizes the scope for mistakes, ensuring product quality and, importantly, enhancing workplace safety.” (Additive Manufacturing Enhances Safety, n.d.) On the other hand, AM systems are self-contained, enclosed, and smaller in stature as well, reducing the risk for operators. AM printers are generally smaller and enclosed, minimizing the risk of accidents associated with large moving parts. Automation in AM processes reduces the need for workers to

be near potentially dangerous equipment. AM widely eliminates the need for tooling which eliminates the need for manual hand work by workers. Thus, reducing the risk of injury when casting, molding etc. As reported by Jung et al. (2023), tooling is 80% of the production cost which is also eliminated completely due to additive manufacturing.

3.3 Reducing Worker Exposure to Hazardous Materials

In classic methods of manufacturing, operators and workers may have to handle harmful chemicals which pose significant health risks. AM minimizes this by using enclosed systems and automated processes. AM reduces health risks by using a self-contained system and in many cases optimized ventilation, in which case no worker or operator must be present in that location or handle certain objects. A journal entry by Huston et al. (2022), features using additive manufacturing to produce uranium objects without an operator being exposed to radioactive material directly other than the beginning and the end of production. Which significantly reduces exposure to radioactive materials.

3.4 Chemical Hazards

AM replaces the need to use hazardous materials by replacing them with nonhazardous materials, specifically in medical and food contact products. Ancillary chemicals, coolants and lubricants for machinery such as lathes and mills are not safe and can cause illness among operators. Using AM can eliminate the use of coolants and lubricants due to the nature of AM technology. Additionally, there are materials, such as amalgams, which can be extremely toxic and dangerous to handle but now that operators are not directly in contact the chance of inhaling, touching, and accidentally carrying tiny amounts of “reduced particles” on them is vastly decreased. In a similar vein there is the matter of scale; AM reduces chemical hazards by using 35–80% less material than traditional methods, minimizing operator's exposure to hazardous waste and ancillary chemicals. (Tay et al., 2024)

3.5 Mechanical Hazards

Mechanical hazards such as heavy components, hot temperatures, and moving machinery are quite common in traditional manufacturing practices. AM with its smaller size in stature and fewer moving parts can reduce these risks compared to large industrial machines. Using AM manufacturers will reduce direct contact with high heat. When the process is automated, the chances of workers being injured are drastically reduced. Traditional manufacturing methods may require significant retooling or adjustments to scale production up or down based on demand. In contrast, additive techniques allow for scalable production without the need for extensive changes to equipment or processes. (Roth, Stefaniak, Murashov, & Howard, 2019)

3.6 Minimization of Human Error, Reduced Need for Heavy Machinery

AM contributes to safer manufacturing by minimizing human error through automated processes. Reducing the need for large machines that are expensive and cannot be customized for different orders. Javaid, et al. (2021) noted “Digital manufacturing technology, such as AM, impacts the environment and minimizes errors during manufacturing positively. It allows engineers to find a suitable approach to perform operations such as digital tooling”. AM systems can replace many systems by streamlining production and reducing direct human contact with production. Which helps in reducing accidents and producing parts as accurately as possible.

4. Case Studies & Applications

AM has been a key competitor in the future of manufacturing with Its ability to reduce occupational hazards when compared with traditional manufacturing being a significant development in the industry. The key findings from various case studies are summarized as follows.

Table 1. Data Collected from Three Different Studies

STUDY	KEY FINDINGS	EXAMPLES	LIMITATION
Springer Metal AM Safety Study (Modupeola, 2023)	Enclosed AM systems significantly reduce mechanical hazards; minimizes operator error and limits exposure to moving parts and toxic chemicals	Aerospace firms use AM to produce lightweight and complex titanium parts without requiring handling of hot materials and moving parts	Ultrafine metal powders increase the risk of inhalation and explosion risk without proper ventilation and inert gas.
CDC/ NIOSH AM Safety Report (NIOSH, n.d.)	AM reduces manual handling and human errors. Closed systems reduce exposure to molten metal and airborne particles.	Metal AM facility used glovebox systems and automated powder management significantly reduces inhalation risk.	Ultrafine particle emissions <100nm require dedicated ventilation systems.
Metal-AM.com Industrial Safety Review (Nair, 2019)	AM machines work in closed off systems with digital interface, reducing thermal, chemical and mechanical injuries.	Automated powder handling via glovebox systems and proper PPE reduces operator exposure to ultrafine particles, high heat and toxic chemicals.	Ignition risks from ultrafine powders but they are covered by inert atmosphere and proper safety processes.

Across studies, AM constantly shows that it has an edge over traditional manufacturing when it comes to producing complicated geometries, reduced material usage and wastage, and most importantly safety of workers in every way. It does this by isolating hazardous processes inside its own enclosure, automated high-risk processes, and minimal manual operations. While there are challenges such as ultrafine <100nm particles, these minor risks can be solved by local exhaust systems with inert gas systems. To summarize, AM has a much safer alternative to conventional processes, specifically for high risk and complex industries such as aerospace and medical device manufacturing.

5. Challenges and Limitations of Implementing AM for Safety

There are, however, several challenges with the implementation of AM which result in stunted adoption. Overcoming recognized challenges will undoubtedly result in a more rapid employment of AM as a primary methodology.

5.1. Physical Limitations

Attaran (2017) noted several different limitations to the adoption of AM including physical, productivity, investment, and regulatory concerns. Starting with production time, in its current state, and in the field of mass production AM is largely less productive than its traditional counterparts, making it difficult for industries to fully transition quickly to AM. Furthermore, considering “Size restrictions” were noted that due to the physical size of 3D printers and that standard printers typically can only produce products that are smaller than the machine itself, the required space for mass production is relatively large compared to traditional methods.

5.2. Regulatory Concerns

Another concern brought by Attaran (2017) is regulations, with the potential for unwell individuals to produce weapons or other undesired items, government regulation will likely be brought forward in the future. The cost is additionally a major concern for companies attempting to adopt AM as a means of production, with a relatively high startup cost and the potential for production-altering regulations there is a potential for risk in adopting AM. For these reasons, there are challenges for companies switching manufacturing methodology.

5.3. Integration Limitations

Ford is an example of a company that has begun to utilize AM technology which has publicly noted operational challenges that have had to be overcome before implementation. In Redford, Michigan, Ford has developed a manufacturing line that is primarily composed of AM methodologies, the benefits of which are rather significant. Automated assembly lines, to the degree where a factory can be left unmanned for several hours a day without issue. However, this was only possible after Ford developed a system that allowed multiple machines to communicate with each other, remarking (Ford, 2022) "Ford developed an application interface program that allows different pieces of equipment to 'speak the same language,' and send constant feedback to each other.". With AM being such a novel technology the integrated infrastructure that many other forms of equipment possess is not currently present and must be produced by the company employing AM. Problems such as these are another paralyzing factor in the conversion of traditional methods to AM methods.

5.4. Particulate Concerns

Particles and their effects on human health are a challenge that AM manufacturers are improving upon; this issue is specifically apparent in AM technologies that use powder beds. In their comprehensive review, Alijagic, et al. (2022) highlights the potential health risks associated with particle emissions in AM processes. It additionally specified that AM has significant industrial advantages; however, the process also releases airborne particles that pose inhalation hazards. AM usually uses ultrafine particles and volatile organic compounds which are dangerous to workers.

Stefaniak et al. (2021) found similar issues with particle emissions in AM. LFAM (Large Format Additive Manufacturing) processes emit airborne particles and volatile organic compounds (VOCs) that pose health risks. A particle counter for the range of 20-100 nm range, detected emissions of all polymers during cleaning with purge compounds. As per Stefaniak et al. (2021) fine particulate matter ($<2.5 \mu\text{m}$) is linked to increased diastolic blood pressure. The document also suggests that inhalation of these particles can also impact cardiovascular health. Animal studies support this concern, Rats that were exposed to ABS particles developed acute hypertension in 3 hours. Additionally, carbon monoxide and dioxide emissions did not correlate well with emissions for most polymers. Only moderate levels of correlation were observed between CO₂ and particle numbers. The study found that wall-mounted exhaust fans were ineffective in controlling emissions, and custom-built canopies also failed to contain them within the enclosure. As per Stefaniak et al. (2021) to mitigate the risk of particulate exposure local exhaust and ventilation in the room is not enough; ventilation located in close proximity to the extruder nozzle or enclosure level exhaust systems are recommended over general room ventilation.

6. Future Directions and Emerging Tools

The future of AM is bright with rapid innovation. The AM process has become largely open source due to many 3D printer manufacturers making them customizable. Open-source inventions and community have helped boost inventions and push technology faster with the help of community and support. Now that almost every engineering college is supporting and providing courses related to AM and 3D printing, a new generation of engineers are pushing forward with the evolution of manufacturing.

Aerospace components have complex geometries and usually are made from advanced materials, such as titanium alloys, nickel superalloys, special steels, or ultrahigh temperature ceramics, which are difficult, costly, and time-consuming to manufacture using conventional processes. Huang et al. 2017 predicts that the allowed complexity reduces cost and eases the prototype stress on engineers and researchers. In the automotive industry using AI and AM, many manufacturers have greatly advanced vehicular designs with precise weight reduction, and complex geometries. Many commercial manufacturers are considering manufacturing interior components using AM techniques.

Thus, even in private and future applications of AM are bright. New and advanced technologies are being utilized daily. While innovative technology is being developed, better AM machines also make it safer for users and operators by reducing harmful pollutants and complex chemicals being released into the air.

7. Conclusion

Additive Manufacturing (AM) represents a possibility of revolutionizing industrial production, manufacturing practices and breaking the stigma of terrible manufacturing conditions. It offers significant benefits over classical manufacturing in terms of safety, efficiency, and the ability to produce complicated objects. By reducing reliance on manual labor, the reduction of human error, toxic exposure and mechanical hazards follows. AM significantly increases operators' safety and overall working conditions. In traditional manufacturing which has toxic chemicals, heavy machinery and higher physical risks. AM streamlines production through automated and digital systems that allow for greater customization without the required customized machines and tools. Although there are challenges such as ultrafine particles and initial startup costs, they are easily manageable with current engineering solutions and technological advancements. The more industries adopt these technologies, the cheaper it becomes for further adoption of this technology. AM is set to become the steppingstone from which Industry 4.0 will upgrade to Industry 5.0; while promoting more sustainable manufacturing across all industries.

8. Disclaimer Statements

Funding: None

Conflict of Interest: None

9. References

- Alijagic, A., Engwall, M., Särndahl, E., Karlsson, H., Hedbrant, A., Andersson, L., & Persson, A. (2022). Particle safety assessment in additive manufacturing: From exposure risks to advanced toxicology testing. *Frontiers in Toxicology*, 4, 836447. <https://doi.org/10.3389/ftox.2022.836447>
- Attaran, M. (2017). The rise of 3-D printing: The advantages of additive manufacturing over traditional manufacturing. *Business Horizons*, 60(5), 677–688. <https://doi.org/10.1016/j.bushor.2017.05.011>
- Berhan, E. (2020). Prevalence of occupational accident and injuries and their associated factors in iron, steel and metal manufacturing industries in Addis Ababa. *Cogent Engineering*, 7(1), 1723211. <https://doi.org/10.1080/23311916.2020.1723211>
- Bureau of Labor Statistics. (2020). Injuries, illnesses, and fatalities. <https://www.bls.gov/iif/home.htm>
- CADimensions. (n.d.). How additive manufacturing enhances safety in modern manufacturing. Retrieved June 17, 2025, from <https://resources.cadimensions.com/cadimensions-resources/how-additive-manufacturing-enhances-safety-in-modern-manufacturing>
- Center for Disease Control. (2024, April 24). Machine safety in the workplace. <https://www.cdc.gov/niosh/machine-safety/about/index.html>
- Ford Motor Company. (2022, March 16). Geared for success: Ford now operates 3D printers autonomously, increasing efficiency and reducing costs. <https://media.ford.com/content/fordmedia/fna/us/en/news/2022/03/16/ford-now-operates-3d-printers-autonomously.html>
- Gibson, I., Rosen, D. W., & Stucker, B. (2021). Additive manufacturing technologies: 3D printing, rapid prototyping,

- and direct digital manufacturing (3rd ed.). Springer. <https://doi.org/10.1007/978-3-030-56127-7>
- Hämäläinen, P., Takala, J., & Saarela, K. L. (2007). Global estimates of fatal work-related diseases. *American Journal of Industrial Medicine*, 50(1), 28–41. <https://doi.org/10.1002/ajim.20411>
- Huang, Y., Leu, M. C., Mazumder, J., & Donmez, A. (2015). Additive manufacturing: Current state, future potential, gaps and needs, and recommendations. *Journal of Manufacturing Science and Engineering*, 137(1), 014001. <https://doi.org/10.1115/1.4028725>
- Huston, D. A., Bergeron, A., Kelly, F., Scott, J., & Corcoran, E. C. (2022, January). Real-time simultaneous temperature and strain measurements of surrogate nuclear fuel pellets using embedded Fiber Bragg Gratings. In *Enabling generational sustainability through science, education, engagement & inclusion. 41st Annual CNS Conference and 46th CNS/CNA Student Conference (Virtual)*, 7–7. <https://www.cns-snc.ca/>
- Javaid, M., Haleem, A., Singh, R. P., Suman, R., & Rab, S. (2021). Role of additive manufacturing applications towards environmental sustainability. *Advanced Industrial and Engineering Polymer Research*, 4(4), 312–322. <https://doi.org/10.1016/j.aiepr.2021.07.005>
- Jung, S., Kara, L. B., Nie, Z., Simpson, T. W., & Whitefoot, K. S. (2023). Is additive manufacturing an environmentally and economically preferred alternative for mass production? *Environmental Science & Technology*, 57(16), 6373–6386. <https://doi.org/10.1021/acs.est.2c04927>
- Khalid, M., & Peng, Q. (2021). Sustainability and environmental impact of additive manufacturing: A literature review. *Computer-Aided Design and Applications*, 18(6), 1210–1232. <http://dx.doi.org/10.14733/cadaps.2021.1210-1232>
- Lai, T. K., Lu, Y., & Ng, T. (2022). Import competition and workplace safety in the US manufacturing sector. *Journal of Economic Behavior & Organization*, 203, 24–42. <https://doi.org/10.1016/j.jebo.2022.08.033>
- Modupeola, D. (2023, December 30). [Title missing]. Springer Nature. Li et al. *Carbon Research* (2024) 3:9 <https://doi.org/10.1007/s44246-023-00097-7>
- Nair, B. V. (2019, Spring). Safety management in metal additive manufacturing. *Metal Additive Manufacturing*. <https://www.metal-am.com/articles/safety-management-in-metal-3d-printing/>
- National Institute for Occupational Safety and Health (NIOSH). (n.d.). Additive manufacturing (3D printing). <https://www.cdc.gov/niosh/manufacturing/additive/index.html>
- Roth, G. A., Stefaniak, A., Murashov, V., & Howard, J. (2019, April 9). Potential hazards of additive manufacturing. NIOSH Science Blog. <https://blogs.cdc.gov/niosh-science-blog/2019/04/09/am/>
- Severe Injury Reports | Occupational Safety and Health Administration. (2015). <https://www.osha.gov/severe-injury-reports>
- Stefaniak, A. B., Bowers, L. N., Martin Jr, S. B., Hammond, D. R., Ham, J. E., Wells, J. R., & Virji, M. A. (2021). Large-format additive manufacturing and machining using high-melt-temperature polymers. Part I: Real-time particulate and gas-phase emissions. *ACS Chemical Health & Safety*, 28(3), 190–200. <https://doi.org/10.1021/acs.chas.0c00128>
- Tay, B. K., Singh, R., Lin, Y. J., Wang, X., & Lee, M. J. (2024). Sustainability assessment of additive manufacturing end-of-life material management. *Resources, Conservation & Recycling Advances*, 20, 100308. <https://doi.org/10.1016/j.jmsy.2023.05.007>

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MEASURING CALIBRATION OF INTERNAL FOOD SAFETY AUDITORS IN A FOOD MANUFACTURING PLANT

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Abstract

The author of this case study collaborated with a food manufacturing facility that produces a range of food products. Food safety audits are crucial for identifying risks and creating a robust food safety culture. An internal food safety audit serves as a continuous improvement tool and prepares for food safety certifications or other standards; however, if auditors are not proficient, food safety audits may be less effective. Measuring internal auditors' calibration can provide value, ensuring that auditors understand the standards and associated food safety risks. This case study analyzed metrics to measure the calibration of internal food safety auditors.

Keywords: *Food Safety; Auditor Calibration, Internal Food Safety Audit, Internal Auditor Training.*

1. Introduction

Information about the competencies and expectations of internal auditors is available. Wilson (2021) refers to food safety auditors' competencies and the areas that they need to know: management system audits, food safety microbiology, food processing fundamentals, food safety issues, and food safety management systems, including the current principles of Hazard Analysis and Critical Control Points (HACCP) and prerequisite programs (PRPs), applicable food laws and regulations of the food processing system being audited, application of auditing principles to food processing systems, and risk and hazard assessment.

Bautista-Smith (2012) emphasized the importance of internal audits as both a compliance tool and a means to enhance process excellence, promote continuous improvement, and increase customer satisfaction. However, in the food industry, part of the auditing process also involves assessing the risk of the three types of hazards that can occur in food products. These are microbiological, chemical, and physical hazards. Microbiological hazards include pathogens and toxins, whereas chemical hazards include mycotoxins, antibiotics, pesticides, and sulfites. Physical hazards comprise any objects or materials that are not part of the product or are part of the product but are intended to be removed (Wilson, 2021).

Coleman (2015) states that for an auditor to be successful, they need to possess knowledge of auditing, quality tools, continuous improvement management, and means of communication, as well as experience in both leading and participating in audits, combined with education and interpersonal skills. However, there is limited information on how to enhance the food safety auditor's knowledge and skills or how to assess the auditor's calibration. Allison and Walker (2004) emphasized the importance of auditors' onboarding training and additional training with specifics regarding the audit program's requirements, report-writing guidance, and foundational information, utilizing a checklist that outlines what is expected and what has already been completed. After onboarding is completed, auditors maintain regular training and professional development.

2. Literature Review

ISO 22000 (2018) describes the requirements of internal audits and auditors. Internal audits must be conducted at regular intervals to verify the organization's compliance with food safety management system requirements and relevant standards. The audit program must consider the importance of the processes and areas to be audited as well as any actions taken as a result of previous audits. The standard refers to the methods defined for the selection of auditors; auditors must be objective. It is necessary to ensure that the nonconformities are addressed.

The facility conducts internal audits within the food industry or at the food establishment itself, typically led by a quality assurance team. These internal audits could reduce the risk if the methods followed were those outlined in the accepted standards or codes. Audit systems currently have limitations in improving food safety (Powell et al., 2013).

Pronovost (2001) discussed the importance of auditor qualification. Internal auditors require fewer qualifications than external auditors, resulting in fewer competencies required. However, an internal auditor requires better interpersonal skills than an external auditor, as they must maintain a working relationship with other employees after the audit. The knowledge required by organizations for internal auditors is often insufficient, resulting in incomplete or unreliable audit conclusions. An internal auditor must have completed at least secondary education and must have some years of experience in positions involving judgment, problem-solving, and communication. This basic knowledge should include quality principles that form the basis of any Quality Management System, general audit concepts and techniques, the audit process, and the process being audited.

Stier (2015) discusses the essential elements of internal audits and states that these are not only good manufacturing practice audits but that they need to include all food safety management system elements, including verification activities, procedures, records, training, education, corrective actions, and the auditor is required to know the process being audited and have the proper education to complete the audit activities.

Rogala et al. (2024) conducted surveys to investigate the factors that affect the credibility of external audits of management systems. Although these refer to external audits rather than internal audits, it is essential to consider their findings as they highlight factors that can be strengthened to enhance internal auditors' competencies. The factors most strongly correlated with credibility assessment were the professional manner in which the audit was conducted and the level of knowledge regarding the activity being audited.

Ab Wahid and Tan (2021) highlight the importance of enhancing external auditor performance through further education and calibration. They conducted a study to investigate whether there is a need to educate external quality auditors further to improve their audit performance, using a survey questionnaire. The findings show that most respondents believe there is a need to improve their education to enhance their audit performance. Auditors' ability to conduct effective audits was lacking in terms of their knowledge, critical thinking skills to solve problems proactively, superior communication, integrity, ethics, and professionalism, as well as objectivity. Although this is primarily true for external auditors, internal auditors also need to evaluate their qualifications and competencies.

Tóth et al. (2024) discuss the risk of internal audits by comparing the results of internal and external audits for food service establishments. Internal audits involve inspections conducted by local staff within the food business, and sometimes, audit efficacy is questioned as failing to uncover food safety issues. The survey indicated that evaluations by external auditors consistently rated food

establishments lower than those by internal auditors and local managers. The differences centered on personal hygiene practices, storage procedures, cleaning methods, and disinfection processes. Based on this data, internal auditors tend to overestimate their adherence to food safety practices; the positive bias in internal audits can pose significant risks to the facility's products and consumers.

Auditor calibration is a process that involves onboarding training, including basic information, as well as customized training for each program type based on auditors' existing skills and experience. Activities that can help with the calibration program include online training, shadowing audits, and witness audits once an auditor has taken all the training required (Allison & Walker, 2004)

Wilson (2021) describes the objective of the audit as determining whether the food safety management systems meet the requirements and whether the controls are adequate and correctly implemented to ensure the production of safe food through the evaluation of hazards, as well as the multiple management systems in the industry from ISO 22000, British Retail Consortium (BRC), International Featured Standards (IFS), and Safe Quality Foods (SQF), which have been benchmarked by the Global Food Safety Initiative to provide audit schemes based on food safety requirements. All of these global standards have internal audit requirements with a preventive focus, highlighting the importance of the internal auditor's role and the internal audit program.

3. Problem Statement

While training and experience are widely recognized as important for enhancing the performance of internal food safety auditors, there is limited research on how to evaluate consistency or agreement among internal auditors. This lack of calibration metrics makes it challenging to ensure audit reliability and comparability across auditing teams.

4. Research Questions

Q1. Are the Scores (Percentage of correct answers) of the group of internal auditors with >1 year of internal auditing experience (Group 2) greater than the group of internal auditors with ≤ 1 year of experience (Group 1)

Q2. Are the SDI (Standard Deviation Index) values of the group of internal auditors with >1 year of internal auditing experience (Group 2) experience less than those than the group of internal auditors with ≤ 1 year of experience (Group 1)

5. Methodology

The method employed was a cross-sectional study with a convenience sample of 21 internal auditors with varying years of experience in internal auditing. The internal auditors self-reported their years of experience in food safety auditing. The internal auditors received a minimum of basic online internal auditor training provided by the company during onboarding, while more experienced auditors had undergone additional external training. Their knowledge was evaluated using a questionnaire comprising 26 questions that included both text-based and color image-based scenarios of nonconformities commonly encountered during internal food safety audits.

The questionnaire was administered onsite, and answers were completed online under supervision in a training room with individual computers. The questions required evaluation if a nonconformance was identified. If a nonconformance was identified, the food safety risk needed to be identified with a scale of 0 as no nonconformance, 1 as an opportunity of improvement (as described in the variables description), 2 as minor risk (as described in the variables description), 3 as major risk (as described in variables description), and 4 as critical risk (as described in variables

description).

A panel of two experienced food safety lead auditors with over 20 years of combined experience and both internal and external auditor certifications reviewed the questionnaire to determine the correct answers. The reference table, which includes questions, scales, and correct answers based on the panel evaluation, is presented in Table 1. The questionnaire is confidential, as it included pictures of the equipment and situations encountered in the specific food manufacturing plant. However, the Question column in Table 1 describes the scenario included in the picture provided to internal auditors for evaluation, and the scale describes the possible answers for the specific questions.

The questionnaire answers were evaluated using an SDI (Standard Deviation Index) to determine how the results aligned with the group mean. Bio-Rad Laboratories (n.d.) consider an SDI value greater than 2 as unacceptable. The questionnaire answers were evaluated as correct or incorrect based on the company's food safety standards and the panel's evaluation.

The data was divided into two groups of auditors. One group consists of auditors with over one year of internal auditing experience (Group 2), while the other group includes auditors with less or one year of auditing experience (Group 1). Separation into groups was essential to determine if a group of auditors with better performance could be utilized for shadowing activities to further improve auditing performance.

The null hypothesis for the SDI values states that there is no significant difference in the SDI values between these groups of auditors. $H_0: \mu_1 = \mu_2$, while the alternative hypothesis indicates the SDI value is smaller for the auditors with more experience (Group 2) than the auditors with ≤ 1 year of experience or $H_a: \mu_1 > \mu_2$. The null hypothesis for correct answers scores states that there is no significant difference between scores from these groups of auditors. $H_0: \mu_1 = \mu_2$, while the alternative hypothesis indicates the correct answers score of the group of auditors with more experience (Group 2) is higher than the group of auditors with ≤ 1 year of experience or $H_a: \mu_1 < \mu_2$.

Table 1. Reference Table with Questions, Scale, and Correct Answers Based on Panel Evaluation

Question Number	Questions	Scale	Correct answers based on Panel
1	Rating production area cleanliness during Start up Inspection	0 not clean, 1- deficient, 2- clean with deficiencies, 4 -clean	1
2	Is the area conformant or non conformant?	Area approved -1, Area not approved- 2	2
3	Rating production area cleanliness during Start up Inspection	0 not clean, 1- deficient, 2- clean with deficiencies, 4 -clean	3
4	Is the area conformant or non conformant?	Area approved -1, Area not approved- 2	1
5	Question related to 18" white line perimeter (internal wall)	Conformance 1 or non conformance 2	1
6	Risk evaluation for previous question	Risk Evaluation: 0-4 (0-none, 1- OFI, 2-minor, 3-major, 4-Critical)	2
7	Question about utensils risk	Conformance 1 or non conformance 2	1
8	Risk evaluation for previous question	Risk Evaluation: 0-4 (0-none, 1- OFI, 2-minor, 3-major, 4-Critical)	2
9	Question about external perimeter	Conformance 1 or non conformance 2	2
10	Risk evaluation for previous question	Risk Evaluation: 0-4 (0-none, 1- OFI, 2-minor, 3-major, 4-Critical)	0
11	Question about food contact tools mishandling	Conformance 1 or non conformance 2	1
12	Risk evaluation for previous question	Risk Evaluation: 0-4 (0-none, 1- OFI, 2-minor, 3-major, 4-Critical)	2
13	Question about food product contact piping condition	Conformance 1 or non conformance 2	1
14	Risk evaluation for previous question	Risk Evaluation: 0-4 (0-none, 1- OFI, 2-minor, 3-major, 4-Critical)	2
15	Question about raw materials conditions and pest risk	Conformance 1 or non conformance 2	1
16	Risk evaluation for previous question	Risk Evaluation: 0-4 (0-none, 1- OFI, 2-minor, 3-major, 4-Critical)	2
17	Question about Quality records completion	Conformance 1 or non conformance 2	1
18	Risk evaluation for previous question	Risk Evaluation: 0-4 (0-none, 1- OFI, 2-minor, 3-major, 4-Critical)	2
19	Question about chemical risk	Conformance 1 or non conformance 2	1
20	Risk evaluation for previous question	Risk Evaluation: 0-4 (0-none, 1- OFI, 2-minor, 3-major, 4-Critical)	2
21	Question with an scenarion without any non conformance	Conformance 1 or non conformance 2	2
22	Risk evaluation for previous question	Risk Evaluation: 0-4 (0-none, 1- OFI, 2-minor, 3-major, 4-Critical)	0
23	Question about Product transportation condition	Conformance 1 or non conformance 2	1
24	Risk evaluation for previous question	Risk Evaluation: 0-4 (0-none, 1- OFI, 2-minor, 3-major, 4-Critical)	2
25	Question about personnel practices	Conformance 1 or non conformance 2	1
26	Risk evaluation for previous question	Risk Evaluation: 0-4 (0-none, 1- OFI, 2-minor, 3-major, 4-Critical)	3

6. Variable Descriptions

Auditor's Years of Experience: Numbers of years practicing internal audits based on their evaluation.

Auditor Group: Auditors with one or fewer years of experience as internal auditors were grouped into Group 1. Auditors with over one year of internal auditor experience were grouped into Group 2.

Questionnaire Responses: Each question in the questionnaire had the possible responses as described in Table 1.

Auditor's Responses for the Evaluation of Risk: Table 1 refers to the risk evaluation for each scenario. The risk evaluation was based on the agreed description of the internal audit procedures. No risk observed scores as 0; Opportunity of improvement scores as 1 and described as fully meeting the standard with potential for element continuous improvement. Minor risk: scores as 2; a non-conformity that shows a lack or deficiency in the food safety and quality system that is unlikely to produce unsatisfactory conditions. Major risk scored as 3 and described as a non-conformity that shows a lack or deficiency in the food safety and quality system with a higher potential to produce unsatisfactory conditions that could carry a food safety and/or quality risk. Critical risk scored as 4 and described as a non-conformity that identifies a breakdown of control(s), critical control points for food safety, and or other process steps likely to cause a significant potential risk in which food safety, direct contamination of manufactured products (Cross Contact, Cross Contamination, Foreign Material).

Correct Answers Scores: Evaluation of each internal auditor's answer to each question based on Table 1. The answers were scored as 1 point if correct and zero if incorrect. The percentage of correct answers was calculated as the total number of points for each auditor divided by the total possible answers (26 questions).

SDI (Standard Deviation Index): Bio-Rad Laboratories (n.d.) refers to SDI as the standard deviation index that measures how close a value is to the target value or group consensus. The SDI value was calculated as the auditor's response minus the consensus group mean, divided by the consensus group deviation. An SDI value of 0 indicates a perfect comparison with the consensus group. A value < 1.25 is acceptable; a value between 1.25 and 1.99 can yield some marginal results, while a result > 2 is considered unacceptable.

7. Results

The internal auditors' responses were summarized in Table 2, which shows each auditor (numbered 1 to 21) and their responses to the 26 questions. The Years of experience and group classification were added to this chart as a reference. All the internal audit responses were compared with the reference Table 1 to determine the Percentage of correct answers, and these results were included in Table 3. The responses were also used to calculate the SDI value, as included in Table 4.

Table 2. Internal Auditors' Responses to Questions

Question #/ Auditor Number	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20	21	22	23	24	25	26	Years Experience	Group
1	3	2	1	2	1	2	1	2	2	0	1	3	1	2	1	3	1	1	1	2	2	0	1	2	1	3	7.0	2
2	2	2	3	1	1	2	1	2	2	0	1	3	1	3	1	2	1	1	1	3	2	0	1	2	1	3	13.0	2
3	2	1	3	1	1	1	1	2	2	0	1	2	1	3	1	4	1	1	1	2	2	0	1	2	1	0	4.0	2
4	2	2	3	1	1	1	1	2	2	0	1	3	1	3	1	3	1	2	1	1	2	0	1	2	2	0	1.0	1
5	2	2	4	1	1	1	1	2	2	0	1	2	1	2	1	3	2	0	1	1	2	0	1	2	1	4	4.0	2
6	3	1	2	2	1	1	1	2	2	0	1	3	1	3	1	3	1	2	1	2	2	0	1	1	2	0	2.0	2
7	1	2	2	2	2	1	1	1	2	0	1	2	1	2	1	2	1	2	1	2	1	1	1	2	1	1	4.0	2
8	2	1	0	2	2	1	1	3	2	0	1	1	1	2	1	4	1	2	1	3	2	1	1	1	1	0	0.0	1
9	3	1	4	1	2	1	1	3	2	1	1	3	1	2	1	3	2	1	1	3	1	2	1	2	1	3	1.0	1
10	0	2	4	1	1	1	1	3	2	0	1	4	1	4	1	3	2	1	1	2	2	0	1	3	2	1	0.1	1
11	2	2	4	1	1	2	1	2	1	2	1	3	1	3	1	4	2	1	1	3	1	2	1	3	1	2	1.0	1
12	3	2	0	2	2	1	2	1	0	0	1	4	1	3	1	3	2	1	1	3	1	3	1	2	1	1	1.0	1
13	2	2	4	1	1	2	2	1	2	1	1	2	1	2	1	2	1	2	1	2	1	1	1	2	1	2	7.0	2
14	2	2	0	2	1	2	1	3	2	2	1	4	1	4	1	4	0	0	1	4	2	0	1	4	1	0	1.0	1
15	0	2	0	2	1	2	1	1	2	0	1	4	2	4	1	4	0	0	1	4	0	0	1	3	1	4	1.0	1
16	4	1	3	2	1	2	1	3	1	2	1	4	1	3	1	3	1	2	1	1	1	3	1	3	1	4	2.0	2
17	4	1	0	2	2	0	1	4	2	0	1	2	1	3	1	4	2	1	1	2	2	0	1	4	2	0	1.0	1
18	3	1	2	1	2	2	2	0	1	2	1	2	1	2	1	2	0	1	1	1	1	2	1	1	1	2	1.0	1
19	3	2	2	1	1	1	2	2	1	0	2	3	2	3	2	3	0	0	2	1	1	0	2	3	0	0	0.0	1
20	3	2	2	2	2	1	2	3	1	2	2	4	2	3	2	4	0	0	2	2	2	0	2	1	2	3	1.0	1
21	2	2		3	2	1	1	1	1	2	0	2	3	1	3	1	4	2	0	1	3	1	2	1	3	1	2.0	2
Mean	2.3	1.7	2.2	1.6	1.4	1.3	1.2	2.0	1.6	0.7	1.0	2.9	1.2	2.7	1.2	3.0	1.2	1.1	1.0	2.1	1.5	0.8	1.1	2.2	1.3	1.6		
StDev	1.1	0.5	1.5	0.6	0.5	0.6	0.4	1.0	0.6	0.9	0.4	0.9	0.5	0.8	0.5	0.9	1.0	0.8	0.4	1.0	0.7	1.0	0.4	0.9	0.6	1.5		
UL (Upper Limit)	2.7	1.9	2.8	1.8	1.6	1.6	1.4	2.5	1.9	1.1	1.2	3.2	1.5	3.0	1.4	3.4	1.6	1.4	1.2	2.6	1.8	1.2	1.3	2.6	1.6	2.3		
LL (Lower limit)	-0.1	-0.3	0.3	-0.2	-0.2	-0.1	-0.2	-0.1	-0.2	0.5	-0.1	-0.5	-0.1	-0.5	-0.1	-0.6	0.3	0.2	-0.1	-0.1	0.0	0.5	-0.2	-0.2	0.0	0.5		

Table 3. Internal Auditors' Correct answers Scores Table

Question # / Auditor Number	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20	21	22	23	24	25	26	Total Points	% Score	Years of experience	Group
1	0	1	0	0	1	1	1	1	1	1	1	0	1	1	1	0	1	0	1	1	1	1	1	1	1	1	20	77%	7.0	2
2	0	1	1	1	1	1	1	1	1	1	1	0	1	0	1	1	1	0	1	0	1	1	1	1	1	1	21	81%	13.0	2
3	0	0	1	1	1	0	1	1	1	1	1	1	1	0	1	0	1	0	1	1	1	1	1	1	1	0	19	73%	4.0	2
4	0	1	1	1	1	0	1	1	1	1	1	0	1	0	1	0	1	1	1	0	1	1	1	1	0	0	18	69%	1.0	1
5	0	1	0	1	1	0	1	1	1	1	1	1	1	1	1	0	0	0	1	0	1	1	1	1	1	0	18	69%	4.0	2
6	0	0	0	0	1	0	1	1	1	1	1	0	1	0	1	0	1	1	1	1	1	1	1	0	0	0	15	58%	2.0	2
7	1	1	0	0	0	0	1	0	1	1	1	1	1	1	1	1	1	1	1	1	0	0	1	1	1	0	18	69%	4.0	2
8	0	0	0	0	0	0	1	0	1	1	1	0	1	1	1	0	1	1	1	0	1	0	1	0	1	0	13	50%	0.0	1
9	0	0	0	1	0	0	1	0	1	0	1	0	1	1	1	0	0	0	1	0	0	0	1	1	1	1	12	46%	1.0	1
10	0	1	0	1	1	0	1	0	1	1	1	0	1	0	1	0	0	0	1	1	1	1	1	0	0	0	14	54%	0.1	1
11	0	1	0	1	1	1	1	1	0	0	1	0	1	0	1	0	0	0	1	0	0	0	1	0	1	0	12	46%	1.0	1
12	0	1	0	0	0	0	0	0	0	1	1	0	1	0	1	0	0	0	1	0	0	0	1	1	1	0	9	35%	1.0	1
13	0	1	0	1	1	1	0	0	1	0	1	1	1	1	1	1	1	1	1	1	0	0	1	1	1	0	18	69%	7.0	2
14	0	1	0	0	1	1	1	0	1	0	1	0	1	0	1	0	0	0	1	0	1	1	1	0	1	0	13	50%	1.0	1
15	0	1	0	0	1	1	1	0	1	1	1	0	0	0	1	0	0	0	1	0	0	1	1	0	1	0	12	46%	1.0	1
16	0	0	1	0	1	1	1	0	0	0	1	0	1	0	1	0	1	1	1	0	0	0	1	0	1	0	12	46%	2.0	2
17	0	0	0	0	0	0	1	0	1	1	1	1	1	0	1	0	0	0	1	1	1	1	1	0	0	0	12	46%	1.0	1
18	0	0	0	1	0	1	0	0	0	0	1	1	1	1	1	1	0	0	1	0	0	0	1	0	1	0	11	42%	1.0	1
19	0	1	0	1	1	0	0	1	0	1	0	0	0	0	0	0	0	0	0	0	0	1	0	0	0	0	6	23%	0.0	1
20	0	1	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	1	0	1	0	0	0	1	4	15%	1.0	1
21	0	1	0	0	0	0	1	0	0	0	0	1	0	0	0	0	0	0	1	0	0	0	0	0	0	0	4	15%	2.0	2

Table 4. SDI value Calculation Table

Question # / Auditor Number	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20	21	22	23	24	25	26	SDI Mean	Years Experience	Group
1	0.7	0.7	0.8	0.7	0.8	1.2	0.5	0.0	0.6	0.7	0.1	0.2	0.4	0.9	0.4	0.1	0.2	0.1	0.1	0.1	0.7	0.7	0.4	0.2	0.4	0.9	0.5	7.0	2.0
2	0.3	0.7	0.6	1.0	0.8	1.2	0.5	0.0	0.6	0.7	0.1	0.2	0.4	0.4	0.4	1.2	0.2	0.1	0.1	0.9	0.7	0.7	0.4	0.2	0.4	0.9	0.5	13.0	2.0
3	0.3	1.4	0.6	1.0	0.8	0.6	0.5	0.0	0.6	0.7	0.1	0.9	0.4	0.4	0.4	1.1	0.2	0.1	0.1	0.1	0.7	0.7	0.4	0.2	0.4	1.1	0.5	4.0	2.0
4	0.3	0.7	0.6	1.0	0.8	0.6	0.5	0.0	0.6	0.7	0.1	0.2	0.4	0.4	0.4	0.1	0.2	1.2	0.1	1.2	0.7	0.7	0.4	0.2	1.1	1.1	0.5	1.0	1.0
5	0.3	0.7	1.2	1.0	0.8	0.6	0.5	0.0	0.6	0.7	0.1	0.9	0.4	0.9	0.4	0.1	0.8	1.4	0.1	1.2	0.7	0.7	0.4	0.2	0.4	1.6	0.7	4.0	2.0
6	0.7	1.4	0.1	0.7	0.8	0.6	0.5	0.0	0.6	0.7	0.1	0.2	0.4	0.4	0.4	0.1	0.2	1.2	0.1	0.1	0.7	0.7	0.4	1.3	1.1	1.1	0.6	2.0	2.0
7	1.2	0.7	0.1	0.7	1.2	0.6	0.5	1.1	0.6	0.7	0.1	0.9	0.4	0.9	0.4	1.2	0.2	1.2	0.1	0.1	0.6	0.2	0.4	0.2	0.4	0.4	0.6	4.0	2.0
8	0.3	1.4	1.4	0.7	1.2	0.6	0.5	1.0	0.6	0.7	0.1	2.0	0.4	0.9	0.4	1.1	0.2	1.2	0.1	0.9	0.7	0.2	0.4	1.3	0.4	1.1	0.8	0.1	1.0
9	0.7	1.4	1.2	1.0	1.2	0.6	0.5	1.0	0.6	0.4	0.1	0.2	0.4	0.9	0.4	0.1	0.8	0.1	0.1	0.9	0.6	1.2	0.4	0.2	0.4	0.9	0.6	1.0	1.0
10	2.2	0.7	1.2	1.0	0.8	0.6	0.5	1.0	0.6	0.7	0.1	1.3	0.4	1.6	0.4	0.1	0.8	0.1	0.1	0.1	0.7	0.7	0.4	0.9	1.1	0.4	0.7	0.1	1.0
11	0.3	0.7	1.2	1.0	0.8	1.2	0.5	0.0	1.0	1.5	0.1	0.2	0.4	0.4	0.4	1.1	0.8	0.1	0.1	0.9	0.6	1.2	0.4	0.9	0.4	0.3	0.6	1.0	1.0
12	0.7	0.7	1.4	0.7	1.2	0.6	1.7	1.1	2.7	0.7	0.1	1.3	0.4	0.4	0.4	0.1	0.8	0.1	0.1	0.9	0.6	2.1	0.4	0.2	0.4	0.4	0.8	1.0	1.0
13	0.3	0.7	1.2	1.0	0.8	1.2	1.7	1.1	0.6	0.4	0.1	0.9	0.4	0.9	0.4	1.2	0.2	1.2	0.1	0.1	0.6	0.2	0.4	0.2	0.4	0.3	0.6	7.0	2.0
14	0.3	0.7	1.4	0.7	0.8	1.2	0.5	1.0	0.6	1.5	0.1	1.3	0.4	1.6	0.4	1.1	1.2	1.4	0.1	1.9	0.7	0.7	0.4	1.9	0.4	1.1	0.9	1.0	1.0
15	2.2	0.7	1.4	0.7	0.8	1.2	0.5	1.1	0.6	0.7	0.1	1.3	1.4	1.6	0.4	1.1	1.2	1.4	0.1	1.9	2.0	0.7	0.4	0.9	0.4	1.6	1.0	1.0	1.0
16	1.6	1.4	0.6	0.7	0.8	1.2	0.5	1.0	1.0	1.5	0.1	1.3	0.4	0.4	0.4	0.1	0.2	1.2	0.1	1.2	0.6	2.1	0.4	0.9	0.4	1.6	0.8	2.0	2.0
17	1.6	1.4	1.4	0.7	1.2	2.3	0.5	2.0	0.6	0.7	0.1	0.9	0.4	0.4	0.4	1.1	0.8	0.1	0.1	0.1	0.7	0.7	0.4	1.9	1.1	1.1	0.9	1.0	1.0
18	0.7	1.4	0.1	1.0	1.2	1.2	1.7	2.1	1.0	1.5	0.1	0.9	0.4	0.9	0.4	1.2	1.2	0.1	0.1	1.2	0.6	1.2	0.4	1.3	0.4	0.3	0.9	1.0	1.0
19	0.7	0.7	0.1	1.0	0.8	0.6	1.7	0.0	1.0	0.7	2.5	0.2	1.4	0.4	1.6	0.1	1.2	1.4	2.5	1.2	0.6	0.7	2.4	0.9	2.0	1.1	1.1	0.5	1.0
20	0.7	0.7	0.1	0.7	1.2	0.6	1.7	1.0	1.0	1.5	2.5	1.3	1.4	0.4	1.6	1.1	1.2	1.4	2.5	0.1	2.0	0.7	2.4	1.3	1.1	0.9	1.2	1.0	1.0
21	0.3	0.7	1.4	2.4	1.2	0.6	0.5	1.1	1.0	1.5	2.7	0.9	3.3	2.2	3.5	2.4	2.9	1.2	2.7	1.2	2.0	0.2	2.4	1.3	2.7	0.4	1.6	2.0	2.0

The results for the internal auditors' correct answer scores' percentages and SDI values were graphed. Figure 1 shows the SDI values for the two groups of auditors: those with ≤ 1 year of experience (Group 1) and those with > 1 year of experience (Group 2). The SDI value was lower for auditors with more experience, and the range was narrower, indicating greater consistency in the results with increased years of experience. Figure 2 shows auditors' Correct Answers Scores" by group, with the Correct Answers Scores being higher for the group with more years of experience.

Figure 1. Internal Auditors' SDI value by Auditors' Group

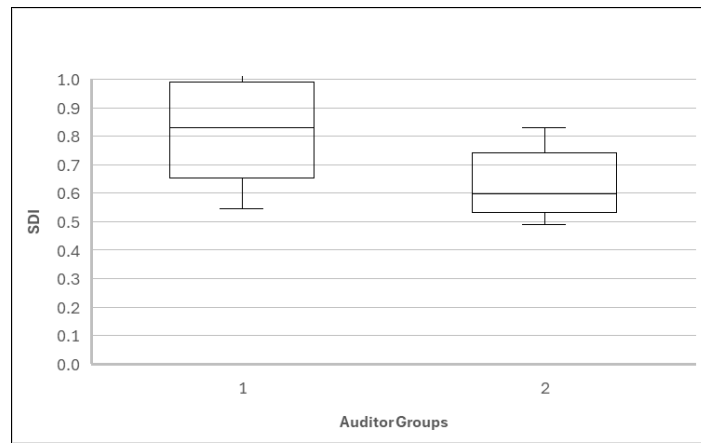
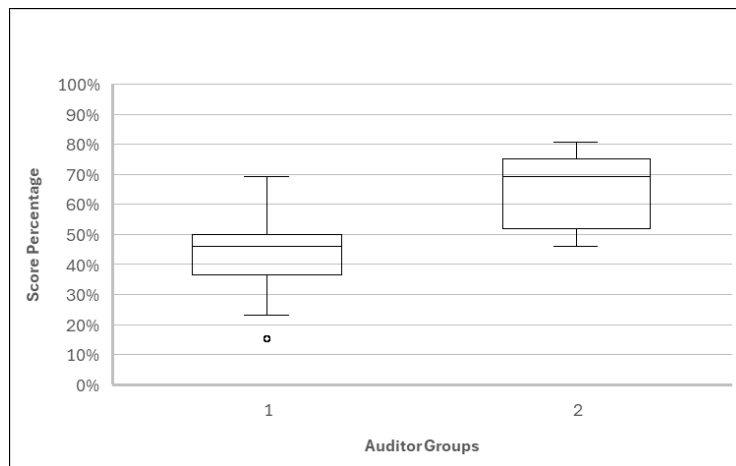


Figure 2: Internal Auditors' Correct Answers Scores by Auditors' Group



The descriptive analysis was summarized in Tables 5 and 6 for Correct Answers scores and SDI values for both groups of internal auditors. The groups have an unequal number of auditors; the mean for scores was larger for Group 2 (> 1 year of experience). However, the standard deviation of this group was also larger. The SDI values comparison in Table 6 by the group showed a lower SDI value for Group 2 (> 1 year of experience), as this value is expected to be closer to 0 when it is closer to the mean; however, the standard deviation was also larger.

Table 5. Descriptive Analysis for Correct Answers Scores

	<i>Group 1</i>	<i>Group 2</i>
Mean	0.44	0.62
Standard Deviation	0.14	0.20
Sample Variance	0.02	0.04
Range	0.54	0.65
Minimum	0.15	0.15
Maximum	0.69	0.81
Count	12.00	9.00

Table 6. Descriptive Analysis for SDI Values

	<i>Group 1</i>	<i>Group 2</i>
Mean	0.83	0.72
Standard Deviation	0.19	0.36
Sample Variance	0.04	0.13
Range	0.65	1.15
Minimum	0.55	0.49
Maximum	1.20	1.64
Count	12.00	9.00

The t-test was calculated and summarized in the following tables for Correct answer scores (Table 7) and SDI values (Table 8). The t-test was used, assuming unequal variances, based on the small sample size and the presence of unequal variances.

Table 7. Scores- t-Test: Two-Sample Assuming Unequal Variances for Internal Auditors' Correct Answers Scores by Group

	<i>Group 1</i>	<i>Group 2</i>
Mean	0.44	0.62
Variance	0.02	0.04
Observations	12.00	9.00
Hypothesized Mean Difference	0.00	
df	14.00	
t Stat	-2.33	
P(T<=t) one-tail	0.02	
t Critical one-tail	1.76	
P(T<=t) two-tail	0.04	
t Critical two-tail	2.14	

The t-statistic was -2.33 with 14 degrees of freedom. The corresponding one-tailed p-value

was 0.02, which was less than 0.05. We concluded that the mean difference in Scores between the groups was greater than zero and rejected the null hypothesis.

Table 8. t-test: Two-Sample Assuming Unequal Variances for Internal Auditors' SDI by Group

	<i>Group 1</i>	<i>Group 2</i>
Mean	0.835	0.720
Variance	0.037	0.129
Observations	12.000	9.000
Hypothesized Mean Difference	0.000	
df	11.000	
t Stat	0.866	
P(T<=t) one-tail	0.202	
t Critical one-tail	1.796	
P(T<=t) two-tail	0.405	
t Critical two-tail	2.201	

The t-statistic was 0.866 with 11 degrees of freedom. The corresponding one-tailed p-value was 0.202, which was greater than 0.05. We concluded that the mean difference in SDI values between groups was not statistically significant.

8. Discussion and Conclusions

Although the results are limited to this group of internal food safety auditors, this case study can be used as an example of how to measure internal food safety auditors' calibration using two metrics: group agreement using an SDI value (Standard Deviation Index) and a score measuring the number of correct answers for situations with similar risks evaluated during the internal audits in a food manufacturing plant.

The groups based on internal auditor experience were important for identifying auditors' performance and internal auditors who could lead other auditors during internal food safety audits. These activities could further improve performance in risk identification and overall audit experience.

The mean for the auditors' "Correct Answers Score" calculated as the Percentage of correct answers was larger for the group with >1 year vs. the group with ≤ 1 year of experience; these results are included in Table 5, Descriptive Analysis for Scores, and Graph 2, with results by a group of auditors. Research question Q1 referred to: Are the Scores of the group of internal auditors with >1 year of internal auditing experience greater than the group of internal auditors with ≤ 1 year for this research question based on the Student's t-test results (Table 7); the p-value 0.02 was smaller than the significance level ($\alpha = 0.05$), indicating that the null hypothesis can be rejected and concluded that the mean difference of correct answers scores between the auditors groups appears to be greater for the group with >1 year of experience.

The SDI values are typically used to assess a group's proficiency. This indicates the extent to which a result deviates from the mean of the comparison group or the level of agreement with the group. The closer the SDI value is to zero, the closer the result is to the group mean. Table 6 shows the

average SDI values for the two groups of auditors, which are larger than zero but less than one (0.83, 0.72). However, an SDI value of <1.25 per chart included in the variable description is acceptable for both groups. Research question Q2 refers to the following: Are the SDI values of the group of internal auditors with >1 year of internal auditing experience less than those of the group of internal auditors with ≤ 1 year of experience? For this research question, based on the t-test (Table 8), the p-value was 0.20, which is larger than the significance level ($\alpha = 0.05$). Therefore, the null hypothesis was not rejected, and it was concluded that the mean difference in the SDI values was not significant.

The two metrics used, the "Correct Answers Score" and the "SDI," focus on different aspects of auditors' evaluation of calibration. The results indicate that auditors' years of experience had a greater effect on the correct answer scores than on the SDI value; both metrics can be important for measuring and comparing the calibration of internal auditors. Although these results were based on pictures of internal audit nonconformities, there are many factors that auditors are exposed to in real situations that can affect their attention to detail and performance compared to these scenarios, where the focus is on a single picture and its risk evaluation.

The years of experience of internal food safety auditors can significantly affect their performance of food safety audits. The auditors in the group with fewer years of experience are not only less trained but also have less exposure to specific food industry situations and associated risks. Food safety auditor activities such as training and auditor' shadowing can help increase the calibration of internal auditors with less experience. However, exercises such as those described in this case study provide metrics for internal auditors to evaluate their calibration.

9. Disclaimer Statements

Anonymity: The research reported in this publication was supported by a food company that desires to remain anonymous. Reported results should not be generalized.

Funding: None

Conflict of interest: None

10. References

- Ab Wahid, R., & Tan, P. L. (2021). *Improving QMS external auditors' audit performance through further education, evaluation and calibration*. *Quantum Journal of Social Sciences and Humanities*, 2(6), 14–27. <https://doi.org/10.55197/qjssh.v2i6.100>
- Allison, K., & Walker, L. (2024, September 8). The importance of auditor calibration. FoodSafetyTech. https://foodsafetytech.com/feature_article/the-importance-of-auditor-calibration
- Bautista-Smith, J. (2012). *Auditing beyond compliance: Using the portable universal quality lean concept*. ASQ Quality Press.
- Bio-Rad Laboratories. (n.d.). *UnityWeb documentation: Standard deviation index (SDI)*. UnityWeb Help. <https://unityweb.qcnet.com/Documentation/Help/UnityWeb/399.htm>
- Coleman, L. B. (2015). *Advanced quality auditing: An auditor's review of risk management, lean improvement, and data analysis*. Quality Press.
- International Organization for Standardization. (2018). ISO 22000:2018—Food safety management systems—Requirements for any organization in the food chain (ISO Standard No. 22000:2018). <https://www.iso.org/standard/65464.html>
- Kotsanopoulos, K. V., & Arvanitoyannis, I. S. (2017). The role of auditing, food safety, and food quality standards in the food industry: A review. *Comprehensive Reviews in Food Science and Food Safety*, 16(5), 760-775. <https://doi.org/10.1111/1541-4337.12293>
- Powell, D. A., Erdozain, S., Dodd, C., Costa, R., Morley, K., & Chapman, B. J. (2013). Audits and inspections are never enough: A critique to enhance food safety. *Food Control*, 30(2), 686–691.

- <https://doi.org/10.1016/j.foodcont.2012.07.044>
- Pronovost, D. (2001). Internal quality auditing [E-book]. ASQ Quality Press.
https://books.google.com/books/about/Internal_Quality_Auditing.html?id=LOuiEAAAQBAJ
- Rogala, P., Kafel, P., & Urbaniak, M. (2024). The credibility of external audits of management systems – the audited enterprises' perspective. *European Business Review*, 36(6), 945-961.
<https://doi.org/10.1108/EBR-09-2022-0184>
- Stier, R. F. (2015). Understanding all the implications of an internal audit: The mantra for all processors should be develop, document, implement, maintain, update and seek to continually improve their food safety management system. *Food Engineering* (Highlands Ranch, Colo.), 87(6), 25.
- Tóth, A. J., Kajtor, M., Illés, C. B., Dunay, A., Vinogradov, S., Battay, M., Süth, M., & Bittsánszky, A. (2024). The effectiveness of food safety self-checking systems in institutional catering the effectiveness of food safety self-checking systems in institutional catering. *Applied Food Research*, 4(2), 100488.
- Wilson, S. (2021). *The ASQ certified food safety and quality auditor handbook* (4th ed.). Quality Press.

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ADDITIVE MANUFACTURING SUPERCHARGING AUTOMOTIVE PARTS FOR MAXIMUM RELIABILITY

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Abstract

Additive manufacturing (AM) is reshaping the automotive industry by offering design flexibility, reduced component weight, & streamlining assembly processes. This paper explores how AM technologies advance the automotive industry through case studies and real-world applications. With AM utilization, automotive industries have achieved improvements in mechanical robustness, system performance, and overall reliability. The paper specifically examines AM's role in prototyping, tooling, material handling, vehicle performance, streamlined assembly, and sustainability within the automotive industry. Challenges such as production speed, material costs, and standardization are also addressed, offering a balanced view of AM's current and future potential.

Keywords: *Additive Manufacturing; Automotive Industry; Real-World Applications; AM Utilization.*

1. Introduction

AM technology is constantly shaping the world around us with its increasing presence, becoming the focus of many researchers and industries. In simplistic terms, “the key to how AM works is that parts are made by adding material in layers...” (Gibson et al., 2015). 3-D printing provides an empty build plate for products to be fabricated, giving the perception that parts are being built out of thin air. This is different to alternative and more common methods like CNC which takes raw material and removes stock to create a functional result. AM technology is known for its ability to minimize waste, match mechanical properties using less material, and its simplicity. Manufacturing using AM technology relies on CAD software as an interface to design products making ideas into reality. CAD is a realm within additive manufacturing that contributes to the quality of the outcome and the efficiency at which it's produced. As CAD continues to develop to be easier to navigate and design, it's becoming more desirable for production in industry and therefore, contributes to AM technologies' viability.

The automotive industry presents itself as one of the most vigorous, high-demanding industries. Statistics found on the International Organization of Motor Vehicles Manufacturers (OICA) Website convey that in 2023, there was a growth of 10% in car production compared to the previous year, reaching a total of 93 million vehicles. To maintain sustainable production while meeting increases in demand, facilities around the globe work towards manufacturing automobile parts utilizing a variety of machinery and tooling. AM technology is a developing field with continuous efforts to make it more compatible with industries like the automotive industry. Modern opportunities of AM in the automotive industry include realms of communication, validation, pre-production,

production, tooling, and end-part production (Sarvankar and Yewale, 2019). Current research provides evidence towards increased involvement between AM technology and the automotive industry due to innovation in AM efficiency, machinery size, and material capabilities. Further discussions of AM drawbacks, potential, and implementation using case studies and relevant research is analyzed in this publication.

2. Manufacturing in the Automotive Industry

The principles that take priority in any manufacturing facility that contributes to an industry the size of the automotive industry can be identified through Porter's Five Forces Analysis; Michael Porter identified five forces that influence an industry. These forces are threat of substitutes, buyer power, supplier power, barriers to entry, and degree of rivalry (Porter, 2008). As the standards change for each of these concepts due to internal and external pressures, "in a market as competitive as the automotive industry, it becomes increasingly important for the organizations to adopt a culture of continuous improvement" (Dias et al., 2019). For the manufacturing sector, adopting machinery requires a deep analysis of how it promotes the mission, scope, and strategy of the automotive company and as a result, its contribution to the principles. Modern issues within the automotive industries include meeting overall increases in demand, desire for customization, limiting the costs of material handling, and condensing vehicle assembly (Micholas et al., 2010). AM technology presents itself as an opportunity to tackle these issues, and with the direction AM research is headed, it's projected to handle certain roadblocks more effectively than traditional methods of manufacturing.

Automotive industries have recognized the potential of AM technology including Volkswagen which took the initiative to dedicate a facility to a majority of its 3-D printing equipment in Autostadt, Wolfsburg; "The facility serves as a center for testing and learning about AM technology, as well as tooling and finished parts manufacturing" (Ibraim & Absadykov, 2024). AM technology has been integrated into research and development programs for automotive companies to experiment with the technology's capabilities investigating concepts of prototyping, tooling, material handling, automobile performance, Just-In-Time (JIT) manufacturing, and sustainability. An analysis of AM applications in the automotive industry will be discussed in further detail to provide a comprehensive understanding of the degree of integration, interest, and potential.

3. Applications of AM in Automotive Industry

Additive manufacturing is being increasingly adopted across various segments of the automotive sector, offering solutions to long-standing manufacturing challenges. Its versatility has enabled innovation in multiple areas from early-stage design to final production. This section explores key applications where AM has made a measurable impact, including prototyping, tooling, material handling, performance, streamlined assembly, and sustainability.

3.1. Prototyping

Since the commercialization of additive manufacturing and with high demand for design flexibility it's common to see AM used to prototype ideas for testing, problem detection, and visualization. The automotive industry has streamlined AM for prototyping applications for years due to its cost saving capabilities. Previous methods of prototyping required investment in machinery and manufacturing methods in order to validate a design's potential, which has proven to be costly and risky. Modern methods of prototyping for automakers rely on partnerships with AM companies to manufacture, model, and test concepts before investment in mass production. "For example, original and aftermarket equipment maker Hyundai Mobis relies on prototyping for design

verification and functional testing, using a Fortus FDM system to help evaluate components such as instrument panels” (Stratasys Inc., 2018). Integrating partnerships with AM technology to prototype has provided automakers with a more sustainable future and has proved to be a requirement for success amongst top automotive manufacturers. Toyota, one of the leading automakers in the past fiscal year, “uses 3D printers to make prototypes of interior trim or to create engines of a transparent material to test that engine oil is normal, and whether the flow is efficient” (Ichida, 2016). Transitioning to AM prototyping provides economic relief with distinct benefits in material properties that prove useful for visualization.

The first commercialized printing method known as stereolithography (SLA) has been a common tool for automotive companies to consider with its consistent promise to deliver results promoting profitability and security. SLA uses photopolymerized resin that hardens during the printing process through selective UV ray exposure. Using SLA has proven to not only be of economic interest but has been known for its ability to accelerate the product development cycle and time-to-market (Chen et al., 2023). Ford, another leading car company known as being a part of the big three, invests in SLA due to the “superiority of this technology in creating new prototype parts with greater speed and efficiency” (Ibraim & Absadykov, 2024). Industrially, automakers have found ways to expand beyond the traditional streamlined approach of using AM technology to prototypes by investing in novel AM machinery. Czipinger used the expansive AM platform to produce both the Blade and 21C models which were assembled using 3D printed components made out of metals and plastics. The Blade began as the prototype model to introduce 3D printing manufacturing for chassis and body elements which was expanded upon in the 21C model to produce 3D printed brake nodes, suspension systems, induction systems, and exhaust systems. Prototyping has expanded to create exceptional depictions of ideas and novel modifications to existing applications that create awareness to stakeholders and the automotive industry. The profitability, flexibility, and innovative realms of the automotive industry all benefited from the inclusion of AM technology for prototyping, and with further technological development, AM is increasing in prevalence.

3.2. Tooling

Additive manufacturing has expanded beyond traditional functionality and into the realm of tooling for automotive purposes. An ongoing concept of interest is to replace prior casting methods with AM casting methods. Current casting methods include green sand casting, centrifugal casting, lost-foam casting, die casting and squeeze casting. Traditional methods of casting are used to produce pistons, engine blocks, valve covers, wheels, transmission housing, carburetors, fan clutches, and more (Goenka et al., 2020). AM casting methods use binder jetting technology to produce sand molds that are proven useful for providing high dimensional accuracy, producing complex geometries, and consolidating assemblies into single components. Back in 2023 it was made public that “Tesla seeks to adopt sand binder jetting, in order to make giant molds that will enable the company to die-cast nearly all the underbody of an EV in one piece rather than the more conventional 400 parts” (P. Madeleine, 2023). Complex part design has become a reality with the introduction of AM machinery providing automakers with an alternative method to manufacture conventionally time-consuming assemblies into single systems.

Desirable characteristics of additively manufactured tooling have become notable for manufacturing high performance vehicles due to its ability to produce complex shapes. For example, Voxeljet has partnered with BMW to test the capabilities of 3D printed sand cores to improve cylinder head design for BMW’s B48 engine. The result was 3D printed water jacket – outlet combi cores that cast cylinder heads with improved engine efficiency and lower fuel consumption (Saldern, 2023). Additively manufactured sand casting was a technique developed so that it could support

common casting methods, building off the backbone of automobile manufacturing. Another lesser-known use of AM includes using powder-bed fusion technology to create metal stamping inserts to produce body panels. Turning to AM technology to produce metal stamping was a direct product of an increase in consumer demand for design flexibility. An analysis between conventional lost foam casting and AM for stamping was conducted conveying powder-bed fusion as the desired technique because of lower operational standards and complexity capabilities. Most importantly “The shorter lead time provided by additive manufacturing proved to be the key decision factor, enabling tool production in due time, considering the rigidity of the milestones imposed on the automotive industry” (Leal et al., 2017). AM tooling has been introduced for unique applications due to comparative advantage while most tooling continues to be made through traditional methods. Research and development programs continue to investigate cost reducing factors, efficiency factors, and innovative opportunities to make it more desirable to the competitive environment of the automotive industry.

3.3. Material Handling

Further consideration for AM integration is being investigated by automotive research teams because of its potential to reduce conflict with material handling. Recommendations for manufacturing facilities to abide by in terms of material handling and facility planning principles include reducing the flow-distance metric, the average work-in-process, and the number of required material handling devices (Saraswat et al., 2015). Automotive companies have begun to consider the capabilities of AM to promote optimal material handling so that the principles are satisfied. In the automotive sector, AM has begun to be used as a method to reduce downtime during mechanical failures. For example, a common mode of mechanical failure in Ford’s assembly line process are the pucks that are important in controlling the movement of conveyors. Ford was able to reduce their costs by replacing broken pucks with 0.50 cent polylactic acid (PLA) printed pucks using FDM systems reducing their annual costs by \$394,000 (Donaldson, 2021). Using AM as a method of internal repair has proven to be profitable for particular assembly line components that are prone to failure and require frequent replacement.

Another avenue to promote efficient and effective material handling has been to Integrate AM into the production process, reducing safety concerns for human involvement in dangerous industrial processes. Ford has taken the initiative to reduce interaction between employees and potentially dangerous machinery increasing automation and security; “Ford is using autonomous technology in addition to 3D printers to take advantage of advanced manufacturing...Autonomous system integration gives the power to run a 3D printer continuously without human interaction, decreasing cost while increasing throughput” (Nayeem & Hossain, 2023). Other automotive brands are beginning to contemplate the incorporation of AM technology for the production of low demand – high-cost parts. Mercedes has been open to considering AM technology with the belief that it could “redefine the supply chain, reduce lead times, transportation costs, and warehousing costs for markets far away from the production facilities and logistic centers. This strategy is mostly focusing on plastic parts with SLS [selective laser sintering] technology for special parts and old parts that are taken out of production” (Edlund, 2017). Internal storage of rare parts led to facility costs and material handling difficulties that could be solved through AM technology involvement. As AM continues to find itself in the automotive sector, the increase in online databases for 3D printing becomes supportive of automotive companies to decrease the internal stock of low volume production parts and tooling; AM has provided solutions by which a “timely response may be achieved through coordination of flexible resources connected to cloud-based networks in response to internal or external environmental changes” (Chung et al., 2018). Demand for customization and

flexibility in the automotive industry is driving the push for AM technology and shaping the material handling system.

3.4. Automotive Performance

A driving factor for the push of AM technology into automotive manufacturing is because of its ability to provide high degrees of design flexibility and lightweight components. What makes AM such a pivotal point in manufacturing is the ability to integrate complex internal geometries like lattices or honeycomb structures that are unable to be manufactured by traditional methods. Investigation of AM capabilities are noticed in design optimization for Bugatti's 3D printed calipers. The Bugatti Chiron is constructed with titanium 3D printed calipers that reduce the weight of the component by about 40% while maintaining its reputable breaking capabilities (Patil, 2021). In the high-performance vehicle market, 3D printed components can drive quality and efficiency changes that increase a vehicle's potential. Porsche, another high-end vehicle manufacturer, utilized Laser Metal Fusion (LMF) as a method to produce aluminum-alloy engine pistons for their performance streetcar the 911 GT2 RS. Optimizing the topology of the engine pistons resulted in a 10 % mass reduction with measures displaying "a potential power increase of the 515 kW biturbo engine by 22 kW accompanied by improved efficiency." (Abele et al., 2021).

BMW also utilized AM to design its S58 engine that will be built into its new line of sport cars. The engine features a 3D printed cylinder head that enables the engine to be lowered to its most optimal weight while maintaining its geometry for thermal management features like built-in coolant channels. The engine is estimated to reach a range of 473-503hp with a torque of 442lb-ft (Anusci, 2019). Automotive companies have recognized the benefits of AM to lightweight their automobiles resulting in better fuel efficiency and greater capabilities. AM has been considered for more affordable vehicle manufacturing as seen from Honda's partnership with Autodesk to redesign their crankshafts. The result was a simulated crankshaft that displayed significant reduction in the crankshaft weight of 30% (Sarzynski et al., 2024). Research and development teams are continuously producing case studies that simulate the benefits of AM for automotive performance. High fuel efficiency is economically profitable for the consumer and represents the quality demand of the market as expectations rise due to the degree of rivalry amongst automakers. As efforts continue to work on producing quicker and cheaper AM machinery, involvement of AM in automotive manufacturing will rise and create a new world of optimization for customers.

3.5. Streamlined Assembly

Competition has pushed automotive companies to explore other avenues of production to maintain relevance. The market is continuously looking for high quality and customizable products from automakers due to reasonable expectations set by automotive companies. To provide desirable products, AM is being used as a production tactic to increase vehicle quality, performance, and customizability. For example, relevant car manufacturer "Mini are as of now allowing customers to design their own inside and outside trim fragments through an online configurator which are then 3D printed and gave to the customer to fit themselves (Mohanavel et al., 2022). AM has introduced itself into the DIY market of vehicle customization as a parallel streamlined process for increased vehicle desirability.

Streamlining AM has also provided companies with capabilities to tap into previously inaccessible markets, allowing room for company growth, opportunity, and development. Recent manufacturing trends using AM has provided reasons for automotive companies to consider its use in everyday production with many European auto manufacturers integrating AM technology in everyday production. Table 1 highlights examples of such integration, showcasing how several

European automotive facilities have already adopted AM technologies.

Table 1. AM production in European automotive manufacturing facilities (Delic et al. 2019)

Country	The use of AM in production processes		
	Yes	No	Total
Austria	1	–	1
Belgium	1	2	3
Czech Republic	5	7	12
Finland	–	1	1
France	16	1	17
Croatia	10	–	10
Italy	10	8	18
Hungary	1	1	2
Netherlands	2	–	2
Germany	16	10	26
Portugal	2	2	4
Romania	–	1	1
Slovakia	1	1	2
Slovenia	–	3	3
Spain	1	–	1
Sweden	–	1	1
UK	14	6	20
Total	78 (62.90%)	46 (37.09%)	124

AM's roots in streamlined production is primarily due to its ability to provide wider accessibility and unique customer interactions with product customization. As AM technology continues to be assessed for its profitability in mainline automotive production, the uses of AM technology have begun to increase. Due to the nature of 3D printing, smaller vehicle components are being printed for streamlined assembly amongst various automakers; "Specialists affirmed that components manufactured with 3D printers are already in use "[made] not with metal materials but only polymer and resin: door handles, some pipes, support assemblies, and design aids" (Nascimento et al., 2022). As AM technology progresses to be more affordable and efficient, use for 3D printing in the automotive industry is expected to become prevalent and replace traditional methods while supporting an industry of high degrees of demand, competition, and power.

3.6. Sustainability

Direction for industry to be environmentally considerate has led towards automotive efforts to replace traditional manufacturing methods with environmentally conscious methods. Current implementation of AM for ecological purposes has a direct relationship with design efforts to lightweight vehicles; "100 kg saved on the mass of a car can save about 9 grams of CO₂ per kilometer, so a reduction of vehicle mass is mandatory, as the most effective measures to reduce CO₂ emission and at the same time maintain performance, driving quality and most of all safety" (Hirsch, 2011). Multiple vehicle manufacturers lightweight their assembly components to decrease fuel consumption and material waste. Recognizing the benefit of lightweighting, "the mini cooper suspension trailing arms were redesigned through topology optimization and the optimized designs weigh 48% less with the strength and performance not compromised. With the help of additive manufacturing, a design that uses less raw materials was achieved and the entire design process was reduced from days to hours" (Chirinda & Matope, 2020). To increase AM's capabilities of producing

sustainable ecofriendly automotive products, active research and development teams are pursuing other alternatives for machine design.

AM machinery has been used as an opportunity to recycle plastics with efforts to produce cyclic processes so that 3D filament materials are reusable; “For example, the Canadian company Re-DeTec has created a machine called the ProtoCycler for small-scale production or for individual use. It is capable of shredding waste plastic and transforming the material into ABS or PLA filaments – two types of polymers that can be used as inputs for 3D printers already on the market (Nascimento et al., 2019). AM displays potential to provide an avenue for upscale recycling efforts that would prove useful to the automotive industry with increases in customer demand, sustainability, and profitability. Other endeavors have been made to consider the material used for AM applications in the automotive sector. Material efforts have led to the manufacturing of fiber-reinforced polymer (FRP) which is “a composite material formed from combining a matrix of polymer resin with either glass (GFRP) or carbon fibers” (Hurt & Schrock, 2016). FRP’s, especially those based on carbon and glass fibers, have been of interest to the automotive sector over the past few decades owing to their low weight and high performance. Optimized FRP’s provide an opportunity to reduce vehicle weight by 25–70% based on the fiber (Sarfraz et al., 2021). Investigations into the material capabilities of AM machinery has benefited its integration into the automotive industry and continues to provide opportunities for automakers to have access to ecofriendly manufacturing options. AM is providing the automotive industry with an opportunity to make their vehicles more desirable through ecofriendly design.

4. Challenges Integrating Additive Manufacturing

With low production speed and high production costs, AM proves to be difficult to integrate into the automotive industry. The automotive industry is highly competitive and requires quick manufacturing methods that result in affordable products. AM has difficulty producing affordable options for industry due to high material costs, especially for metal powder, and its inability to produce many parts in a timely manner that’s comparable to traditional methods; “Typically, automotive parts are produced in relatively high volumes, for which Additive Manufacturing is far less competitive” (Delic et al., 2019). AM cannot keep up with the levels of demand that the automotive industry requires reducing its profitability. Methods of metal AM is the technique that finds the most opportunity in the automotive industry due to the wide range of factors it supports but, the method of powder production causes many difficulties. Metal powder production is costly and risky for consumption due to uncertainties in powder quality directly affecting the 3D printing process. One of the most critical factors impacting cost and consistency in metal AM is the quality of the powder used in the process. Figure 1 illustrates the relationship between powder testing, powder properties, and their influence on process instabilities, highlighting key issues that contribute to defects and inefficiencies in AM.

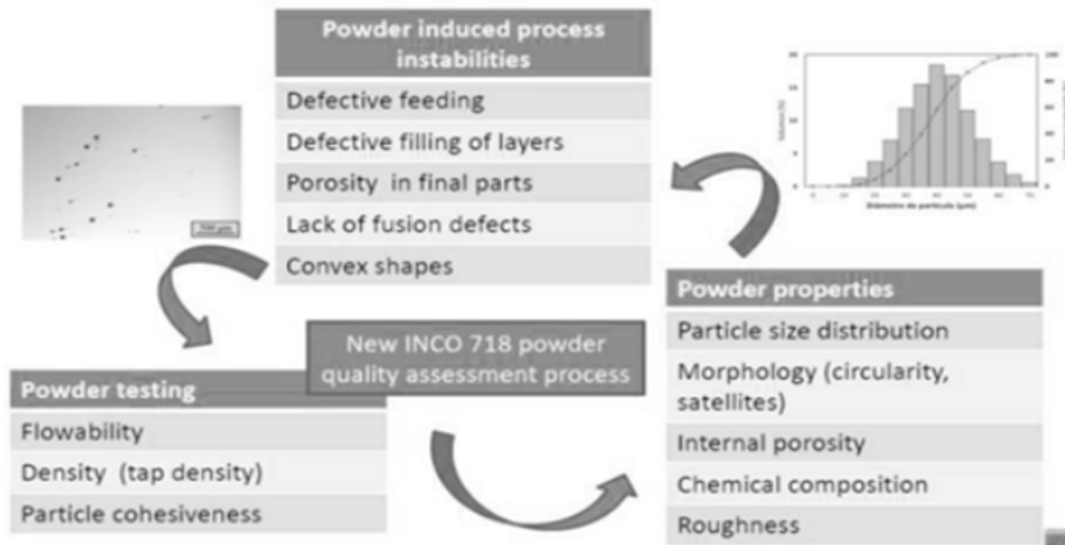


Figure 1. Powder based 3D printing issues (Duda & Raghavan, 2018)

Investigations into methods for AM problem-solving have increased trust in the automotive community of AM machinery but there are still numbers of uncertainties about the technology that haven't been solved or discovered yet. AM technology lacks a standardization of conditions that must be followed across all AM machinery resulting in distrust of the process and as a consequence quicker research and development; "Most of the defects that arise in conventional manufacturing methods are known, but a proper understanding of defects in AM processes is lacking and is a constant research topic" (Parvanda & Kala, 2022). There are no standardized AM specific methods for conducting interlaboratory studies of AM materials, the underlying factors responsible for machine-to-machine variability, and the qualification of raw materials, including metal powders, is limited. (Nascimento et al., 2022). AM shows promise for the automotive industry but still requires levels of development that have not yet been reached to be considered as an opportunity to replace traditional methods like CNC and casting.

5. Conclusion

AM processes are becoming more applicable to the automotive industry with modern research and development. Within years to come there is a greater chance that additive manufacturing will take over multiple traditional manufacturing techniques reshaping the automotive industry. AM is constantly becoming more accessible, affordable, and efficient as modern technology develops to solve industrial conflict. The relationship of the automotive industry with the market continues to grow in competition with AM presenting an opportunity to access new avenues to increase profitability and relevancy. With industry 4.0 and 4D automated printing technology, AM will be more capable of solving industrial issues that are important to automotive manufacturing.

6. Disclaimer Statements

Funding: None

Conflict of Interest: None

7. References

- Abele, D., Ickinger, F., Schall, V., & Klampfl, M. (2021). Additive manufacturing of high-performance powertrain components. *MTZ Worldwide*, 82(2), 14–19. <https://doi.org/10.1007/s38313-020-0595-x>
- Anusci, V. (2019, March 4). BMW's new S58 engine features cylinder head made with 3D printing. *VoxelMatters*. <https://www.voxelmatters.com/bmw-s58-engine-3d-printed-cylinder/> (Accessed 17 June 2025)
- Chen, L., Ng, N. P. H., Jung, J., & Moon, S. K. (2023, December). Additive manufacturing for automotive industry: Status, challenges and future perspectives. In *2023 IEEE International Conference on Industrial Engineering and Engineering Management (IEEM)* (pp. 1431–1436). IEEE. <https://doi.org/10.1109/IEEM58616.2023.10406820>
- Chirinda, G. P., & Matope, S. (2020, December). The lighter the better: Weight reduction in the automotive industry and its impact on fuel consumption and climate change. In *Proceedings of the 2nd African International Conference on Industrial Engineering and Operations Management* (pp. 7–10). <https://doi.org/10.46254/AF02.20200179>
- Chung, B. D., Kim, S. I., & Lee, J. S. (2018). Dynamic supply chain design and operations plan for connected smart factories with additive manufacturing. *Applied Sciences*, 8(4), 583. <https://doi.org/10.3390/app8040583>
- Delic, M., Eysers, D. R., & Mikulic, J. (2019). Additive manufacturing: Empirical evidence for supply chain integration and performance from the automotive industry. *Supply Chain Management: An International Journal*, 24(5), 604–621. <https://doi.org/10.1108/SCM-12-2017-0406>
- De Mattos Nascimento, D. L., Mury Nepomuceno, R., Caiado, R. G. G., Maqueira, J. M., Moyano-Fuentes, J., & Garza-Reyes, J. A. (2022). A sustainable circular 3D printing model for recycling metal scrap in the automotive industry. *Journal of Manufacturing Technology Management*, 33(5), 876–892. <https://doi.org/10.1108/JMTM-10-2021-0391>
- Dias, P., Silva, F. J. G., Campilho, R. D. S. G., Ferreira, L. P., & Santos, T. (2019). Analysis and improvement of an assembly line in the automotive industry. *Procedia Manufacturing*, 38, 1444–1452. <https://doi.org/10.1016/j.promfg.2020.01.143>
- Duda, T., & Raghavan, L. V. (2018). 3D metal printing technology: The need to re-invent design practice. *AI & Society*, 33(2), 241–252. <https://doi.org/10.1007/s00146-018-0809-9>
- Edlund, P. (2017). Additive manufacturing in low-volume production—Business case for metal components. <https://publications.lib.chalmers.se/records/fulltext/251245/251245.pdf> (Accessed 16 June 2025)
- Gibson, I., Rosen, D., & Stucker, B. (2015). Design for additive manufacturing. In *Additive Manufacturing Technologies: 3D Printing, Rapid Prototyping, and Direct Digital Manufacturing* (pp. 399–435). Springer. <https://doi.org/10.1007/978-1-4939-2113-3>
- Goenka, M., Nihal, C., Ramanathan, R., Gupta, P., & Parashar, A. (2020). Automobile parts casting—Methods and materials used: A review. <https://doi.org/10.1016/j.matpr.2020.03.381>
- Hirsch, J. (2011). Aluminium in innovative light-weight car design. *Materials Transactions*, 52(5), 818–824. <https://doi.org/10.2320/matertrans.L-MZ201132>
- Ibraim, A. S., & Absadykov, B. N. (2024). 3D-printing in the automotive industry. *Bulletin of LN Gumilyov Eurasian National University Technical Science and Technology Series*, 148(3), 206–218. <https://doi.org/10.32523/2616-7263-2024-148-3-206-218>
- Ichida, Y. (2016). Current status of 3D printer use among automotive suppliers: Can 3D printed-parts replace cast parts. *IFEAMA SPSCP*, 5, 69–82. https://ifeama.org/ifeamaspscp/selected%20papers/13th%20in%20Ulaanbaatar/13th%2006%20%20Y_Ichida_final.pdf (Accessed 18 June 2025)
- Leal, R., Barreiros, F. M., Alves, L., Romeiro, F., Vasco, J. C., Santos, M., & Marto, C. (2017). Additive manufacturing tooling for the automotive industry. *The International Journal of Advanced Manufacturing Technology*, 92, 1671–1676 <https://doi.org/10.1007/s00170-017-0239-8>
- Michalos, G., Makris, S., Papakostas, N., Mourtzis, D., & Chryssolouris, G. (2010). Automotive assembly technologies review: Challenges and outlook for a flexible and adaptive approach. *CIRP Journal of Manufacturing Science and Technology*, 2(2), 81–91. <https://doi.org/10.1016/j.cirpj.2009.12.001>

- Mohanavel, V., Priyadharshan, R., Ravichandran, M., Sivanraju, R., Velmurugan, P., & Subbiah, R. (2022). The role and application of 3D printer in the automobile industry. *ECS Transactions*, 107(1), 12001. <https://doi.org/10.1149/10701.12001ecst>
- Nascimento, D. L. M., Alencastro, V., Quelhas, O. L. G., Caiado, R. G. G., Garza-Reyes, J. A., Rocha-Lona, L., & Tortorella, G. (2019). Exploring Industry 4.0 technologies to enable circular economy practices in a manufacturing context: A business model proposal. *Journal of Manufacturing Technology Management*, 30(3), 607–627. <https://doi.org/10.1108/JMTM-03-2018-0071>
- Nayeem, A. M., & Hossain, M. M. N. (2023). Usage of additive manufacturing in the automotive industry: A review. *Bangladesh Journal of Multidisciplinary Science Research*, 8(1), 9–20. <https://doi.org/10.2139/ssrn.5161495>
- Parvanda, R., & Kala, P. (2023). Trends, opportunities, and challenges in the integration of additive manufacturing with Industry 4.0. *Progress in Additive Manufacturing*, 8(3), 587–614. <https://doi.org/10.1007/s40964-022-00351-1>
- Patil, K. (2021). 3D-printed titanium brake caliper in high-performance vehicles. In *The 1st Advanced Manufacturing Student Conference (AMSC21)*, Chemnitz, Germany, 15–16 July 2021 (p. 62). https://www.researchgate.net/profile/Dominik-Krumm/publication/364358621_Conference_proceedings_of_the_advanced_manufacturing_student_conference/links/634f94df6e0d367d91a986f2/Conference-proceedings-of-the-advanced-manufacturing-student-conference.pdf#pag (Accessed 16 June 2025)
- P., M. (2023, September 21). Tesla turns to 3D printing to “reinvent carmaking.” *3Dnatives*. <https://www.3dnatives.com/en/tesla-turns-to-3d-printing-to-reinvent-carmaking-190920234/> (Accessed 18 June 2025)
- Production statistics. (n.d.). OICA. <https://www.oica.net/category/production-statistics/2023-statistics/> (Accessed 16 June 2025)
- Sarzyński, B., Śnieżek, L., & Grzelak, K. (2024). Metal additive manufacturing (MAM) applications in production of vehicle parts and components—A review. *Metals*, 14(2), 195. <https://doi.org/10.3390/met14020195>
- Saldern, F. von. (2025, January 27). Voxeljet & Loramendi demo ICP line at BMW. Voxeljet. <https://www.voxeljet.com/press-releases/voxeljet-and-loramendi-show-icp-additive-series-production-line-in-action-at-bmw/> (Accessed 17 June 2025)
- Saraswat, A., Venkatadri, U., & Castillo, I. (2015). A framework for multi-objective facility layout design. *Computers & Industrial Engineering*, 90, 167–176. <https://doi.org/10.1016/j.cie.2015.09.006>
- Sarvankar, S. G., & Yewale, S. N. (2019). Additive manufacturing in automobile industry. *International Journal of Research in Aeronautical and Mechanical Engineering*, 7(4), 1–10. <https://ijrame.com/wp-content/uploads/2019/04/V7i401.pdf> (Accessed 17 June 2025)
- Shehab, E., Meirbekov, A., Amantayeva, A., Suleimen, A., Tokbolat, S., & Sarfraz, S. (2021). A cost modelling system for recycling carbon fiber-reinforced composites. *Polymers*, 13(23), 4208. <https://doi.org/10.3390/polym13234208>

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