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Digital Transformation of the Kiswah: A Framework for Integrating Additive Manufacturing in Sacred Gold Thread Embroidery - The Case of Al-Kaaba

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Abstract

The Kiswah, the black silk cover of the Holy Kaaba in Makkah, is among the most venerated textile artefacts in the Islamic world. Its calligraphic and geometric ornamentation is traditionally executed in a couched gold-thread embroidery technique known as zari, applied over cotton padding to produce the raised thuluth script that protrudes approximately two centimetres from the fabric surface. The annual production of the Kiswah engages approximately 200 to 300 skilled artisans for an eight to twelve-month cycle and consumes between 120 and 200 kilograms of gold and silver thread, at a reported cost in excess of GBP 3.3 million. While the spiritual, cultural, and aesthetic value of this craft is unquestioned, three converging pressures - the deterioration of metallic threads under Makkah's extreme climatic conditions, the contraction of the traditional craft labour pool, and the sustainability ambitions articulated within Saudi Vision 2030 - have together created a strategic opening to investigate complementary digital production methods. This paper proposes a conceptual framework for integrating additive manufacturing (AM) into the production pipeline of sacred Kiswah ornamentation, while preserving its religious sanctity, traditional aesthetics, and tactile depth. The framework is structured around four interlocking domains: (i) sacred and cultural fidelity, (ii) material and environmental performance, (iii) production economics and sustainability, and (iv) hybrid craft-digital workflows. Each domain is operationalised through a set of performance criteria adapted from the SAFE model (Social, Aesthetic and Affordability, Functionality, Environment) of Almerbati et al. (2014). The framework does not seek to replace artisanal embroidery, but rather to define the conditions under which AM-produced ornamental elements may legitimately complement or substitute for selected components of the traditional process. The paper concludes with a roadmap for empirical validation, identifying material classes (filled photopolymer resins, metal-filled PLA, and technical ceramics) most likely to satisfy the combined sacred, functional, and environmental requirements of the Kiswah.

Keywords: Kiswah; Al-Kaaba; Additive Manufacturing; Gold Thread Embroidery; Zari; Thuluth Calligraphy; Cultural Heritage; Digital Craftsmanship; Vision 2030; Sustainable Textiles.

Introduction

The Holy Kaaba in Makkah is the spiritual focal point of more than 1.9 billion Muslims worldwide and the qiblah toward which prayer is oriented five times daily. The cubic structure is enveloped each Hijri year by the Kiswah, a ceremonial covering of black silk measuring approximately 658 square metres, upon which Qur'anic verses are embroidered in raised gold and silver thread within a horizontal calligraphic belt known as the Hizam. The technical, aesthetic, and devotional sophistication of this object places it among the most demanding works of religious textile craftsmanship in the world.

Despite the cultural prestige of Kiswah production, the contemporary practice faces material

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and structural pressures that warrant scholarly attention. First, gold and silver metallic threads - even when produced as wrapped composite filaments combining a synthetic core with a metallised coating - undergo measurable optical and structural degradation under the temperature, humidity, and ultraviolet exposure conditions characteristic of Makkah's microclimate. Second, the supply of artisans capable of executing the demanding zari and dabka techniques required for the raised thuluth script is contracting, a pattern observed across many traditional craft sectors in the Gulf region. Third, the strategic priorities articulated in Saudi Vision 2030 explicitly call for the integration of advanced manufacturing technologies into heritage industries to enhance sustainability, reduce material waste, and develop national capabilities in design and digital production.

Against this background, additive manufacturing (AM) emerges as a candidate technology for selected stages of Kiswah ornamentation. AM offers several characteristics that align well with the functional and aesthetic demands of raised calligraphic embroidery: precise dimensional control, the ability to reproduce complex geometric forms repeatably, the potential for material formulations with engineered colour and surface properties, and substantially lower per-unit labour intensity than hand embroidery. However, AM also introduces significant questions concerning religious legitimacy, tactile authenticity, surface adhesion to silk substrates, and long-term performance in outdoor sacred contexts.

This paper does not attempt to resolve these questions empirically. Rather, it advances a conceptual framework - the Sacred Additive Manufacturing (SAM) framework - that defines the dimensions along which any proposed AM intervention in Kiswah production must be evaluated, and the relationships between those dimensions. The framework is intended to serve as a normative and analytical reference for subsequent empirical work, including the companion applied study presented in Paper 2 of this research programme.

Research Aim and Objectives

This paper aims to develop a defensible, multi-criteria framework for evaluating the integration of additive manufacturing into Kiswah ornamentation production. The specific objectives are:

- To articulate the religious, cultural, and aesthetic constraints that any digital intervention in Kiswah production must respect.
- To identify the material and environmental performance criteria that AM-produced ornamentation must satisfy in the Makkah context.
- To map the economic, labour, and sustainability dimensions of a hybrid traditional-digital production model.
- To synthesise these dimensions into an integrated framework that can guide both empirical validation and policy decision-making.
- To recommend candidate material classes and AM process families warranting empirical investigation.

Scope and Limitations

This paper is conceptual in character. It draws upon documentary evidence from the Kiswah Factory at Makkah (Masna' al-Kiswah), the existing scholarly literature on AM in heritage and textile contexts, and the author's direct observation of traditional production. It does not present primary experimental data on material performance; that is the focus of the companion paper. The framework is developed specifically with reference to the Kiswah of the Kaaba and is not intended to be generalised, without modification, to other sacred textile contexts.

Background and Context

The Kiswah: Historical and Material Overview

The tradition of covering the Kaaba with a ceremonial textile, known as the Kiswa, predates Islam and carried deep religious, political, and social significance in the pre-Islamic era. It was regarded as an act of veneration and righteousness (Basahih, 2021), often performed twice annually as either a gift or the fulfilment of a vow. With the advent of Islam, this practice gained heightened importance, symbolising religious devotion, ideological loyalty, and closeness to God (Basahih, 2021).

Historical accounts trace the first Islamic Kiswa to the Prophet Muhammad in the tenth year of the Hijra, when Yemeni cloth was used. Successive caliphs institutionalised the tradition, with Egypt emerging as the principal centre of production from the tenth century AH, supplying high-quality fabrics such as brocade, Coptic textiles, Yamani Burud, and even leather. The colour conventions of the Kiswa varied across eras—red, green, and white were all employed—before the black covering became standard under Ottoman and later Saudi custodianship (Basahih, 2021).

The practice was embraced by diverse cultures, including Egypt, the Ottoman Empire, Yemen, and Saudi Arabia, each contributing distinctive decorative and aesthetic values. In modern times, King Abdulaziz established the first Saudi Kiswa factory in Makkah in 1926, with the inaugural locally produced covering installed the following year. Thus, the Kiswa embodies both continuity and transformation: a textile tradition rooted in pre-Islamic ritual, enriched by Islamic devotion, and sustained across centuries as a symbol of reverence, craftsmanship, and cultural identity (Basahih, 2021).

The contemporary Kiswah is composed of a black silk ground fabric of approximately 658 square metres, divided into 47 panels. The ornamental Hizam, a horizontal calligraphic belt approximately 95 centimetres in width, encircles the structure two-thirds of the way up its elevation and bears Qur’anic verses in raised thuluth script. The calligraphy is executed by laying cotton or jute cords upon the silk to establish the curvilinear forms of the script, after which gold and silver metallic threads are couched over the cords using a technique that produces relief of approximately two centimetres above the ground plane. Additional ornamental medallions, botanical motifs, and the names of God and the Prophet appear in the corners and at the door of the Kaaba (the Sitarah).

Figure 1. Detail of the gold-thread embroidered ornamental medallion on the Kiswah, showing the characteristic raised thuluth calligraphy of the Kaaba covering. The two-tone work combines couched gold zari thread for the principal letterforms with silver outlining for definition. Source: Author’s photographic record.

Egila and Salama (2026) examined two preserved samples of Kiswah at the Egyptian Textile Museum and the National Museum of Egyptian Civilisation in Fustat, tracing the journey of the Kiswah from its production in Dar al-Khurunfush to its arrival at the Two Holy Mosques. Out of six designs, one was preferred by survey participants for its suitability in fashion design to enhance the identity of the Meccan woman (Alshibi & Maghrabi, 2020). Alashari, Hamzah, and Marni (2021) cited the Qur’anic verse, “The first house was placed for people who are blessed with the blessing and guided to the two worlds” (Āl ‘Imrān: 96), recalling that God commanded Prophet Abraham and his son to build the Kaaba. Before the emergence of Islam, kings competed to cloak the Kaaba in the most beautiful ornamental cloth across ancient and contemporary times.

The Kaaba remained largely unchanged until Mecca was inhabited by certain Arab tribes, among them the Amalekites, who undertook repairs when time and natural factors had caused damage. For much of this earlier period, the Kaaba stood without a roof. It was Qusay ibn Kilab

- an ancestor of the Prophet Muhammad - who first roofed the sanctuary, marking a significant stage in its architectural development. Custodianship was later entrusted to the tribes of Jurhum and Khuza'a, during which the tradition of clothing the Kaaba was upheld by Arab nobility throughout the pre-Islamic era. The Himyarite king is regarded as the first to clothe the Kaaba before the advent of Islam. When custodianship eventually passed to the Quraysh, Qusay ibn Kilab personally undertook the honour of clothing the sanctuary; in time, this responsibility was embraced collectively by the Quraysh community, transforming it into a shared expression of reverence and prestige.

Following the advent of Islam, the Prophet Muhammad clothed the Kaaba in Yemeni fabric, and subsequent caliphs continued the tradition. Caliphs Abū Bakr and 'Umar covered it with fine Qabātī fabric, while Caliph 'Uthmān ibn 'Affān employed both Qabātī and Yemeni cloth and is regarded as the first Muslim leader to clothe the Kaaba with two layers of fabric, one placed above the other. During the Umayyad era, Caliph Mu'awiya ibn Abī Sufyān introduced silk coverings, a practice continued by Yazīd ibn Mu'awiya and 'Abd al-Malik ibn Marwān. The Abbasid caliph al-Mahdī, during Hajj in 160 AH, decreed that only one covering should remain at any time to prevent structural strain from accumulated layers. Later Abbasid rulers introduced varied colours - red, white, green, and black - until black became the standard.

From the Mamluk and Ottoman periods, Egypt assumed responsibility for producing the Kiswah, dedicating villages as endowments and sending elaborately decorated cloths annually. Ottoman sultans oversaw both external and internal Kiswahs, with the latter produced in Istanbul. In modern times, King Abdulaziz established a Kiswah factory in Mecca in 1346 AH, employing master craftsmen; King Faisal later modernised the facility, equipping it with advanced technology while preserving manual artistry for its highest aesthetic value. Since then, Saudi Arabia has maintained the honour of producing the Kiswah, blending tradition with innovation to uphold the sanctity of the Kaaba. A historical study by Alashari (2022) further revealed that Bin Nasser bin Qalawun, king of Egypt, was the first to approve the waqf system for funding the cloak of the Holy Kaaba, and that the Sultans of the Mamluk state gave high levels of care to the Holy Kaaba and its cladding.

The Gold Thread Material: Properties and Vulnerabilities

The gold thread used in Kiswah embroidery is a composite filament rather than solid metal. In typical zari construction, a fine silk or polyester core is wrapped with a flat metallic strip (called a gilt strip) that has been gilded or electroplated with gold or silver onto a base substrate, typically copper or silver alloy. This composite construction provides flexibility for stitching while presenting a metallic optical surface. However, the same construction is the source of the material's principal vulnerabilities.

The factors affecting the long-term performance of metallic embroidery thread on the Kiswah may be summarised as follows. Ultraviolet radiation, intense in Makkah owing to its low latitude and high annual sunshine hours, accelerates oxidation of the metallic surface and degrades any protective lacquer coatings, leading to tarnish and chromatic shift toward duller, more orange or brown tonalities. Atmospheric humidity, although relatively low in Makkah's arid climate, combines with episodic rainfall and the perspiration of millions of pilgrims to introduce moisture-mediated corrosion of the silver substrate beneath the gold gilding, producing the characteristic blackening of aged silver thread. Mechanical abrasion from contact with pilgrims, who traditionally seek tabarruk (blessing) by touching or kissing the Kiswah where accessible, contributes to localised wear of the raised embroidery. Thermal cycling, with surface temperatures on the black Kiswah recorded in excess of 70 degrees Celsius under direct summer

sun, induces differential expansion between the silk substrate, the cotton padding cords, and the metallic wrapping, producing micro-fractures in the gilt strip over time. Finally, the very weight of the metallic thread - gold and silver bullion contributes a substantial portion of the Kiswah's overall mass - places sustained tensile stress on the silk substrate, which itself is photodegraded by ultraviolet exposure.

Photodegradation of the Kaaba silk cover was detected by Elnagar, Tera, and Elamoundy (2012), when it was exposed directly to the prevailing environmental conditions at Mecca for one year and at different successive periods. Climate-change threats to the Kaaba cover include weakening of the silk fibres by intense heat (making them more prone to tearing and breakage), fading of the Kiswah's vibrant colours - especially the gold and silver embroidery - by ultraviolet radiation, mould and mildew damage from high humidity, and embedding of sand and dust particles causing abrasion and staining due to dust storms (KiswaIslamic, 2025). Comparable vulnerabilities have been reported for Spanish and Portuguese historical metal threads by Duran, Perez-Maqueda, and Perez-Rodriguez (2019), and for two metallic threads from traditional Malay textiles by Kamarulzaman, Taif, Ab Kadir, and Abdul (2025).

These vulnerabilities are partially the reason why the Kiswah is replaced annually rather than being conserved indefinitely. They also establish the performance benchmark that any candidate replacement material must meet or exceed: a service life of at least one Hijri year under outdoor exposure in Makkah, with retention of metallic visual character and structural integrity throughout that period.

Figure 2. Close-up of a single embroidered medallion, illustrating the depth and luminosity of the couched gold-thread surface. The directional sheen visible across the letterforms is produced by the parallel orientation of individual thread bundles - an optical signature that any candidate digital substitute must convincingly reproduce. Source: Author's photographic record.

Direct polymer deposition onto textile substrates, investigated by researchers such as Brinks, Warmoeskerken, Akkerman, and Zweers (2013) and Melnikova, Ehrmann, and Finsterbusch (2014), refers to the direct application of functional polymers (such as PLA or conductive polymers) onto fabrics to create hybrid materials with both textile and hard-surface characteristics. Brinks et al. (2013) defined this as 3D polymer deposition, aiming to build three-dimensional polymers directly on surfaces in a programmed way. However, the free-movement nature of fibres makes direct bonding difficult; successful bonding requires the polymer to penetrate the fabric structure. This technology adds value by combining the comfort of textiles with functional, hard-wearing components for applications such as smart clothing. Melnikova et al. (2014) showed that 3D printing on textiles is effective if the polymer material is compatible with the specific textile printer: a minimum material thickness is required for weft-knitted structures to ensure strength, and the distance between stitches is important for structural integrity. Their research also explored Selective Laser Sintering (SLS) systems for creating complex geometries on fabrics, focusing on integrating conductive polymers with textiles for smart-textile applications. The core principles for successful deposition are therefore adhesion optimisation, drape maintenance, and appropriate selection of application areas. Sanatgar, Campagne, and Nierstrasz (2017) further noted significant differences in the influence of 3D-printing processing parameters on the adhesion properties of different polymers.

This technology commonly utilises Fused Deposition Modelling (FDM) 3D printing to create coatings, functional elements, or complex 3D structures on woven and knitted materials (Pei, Shen, & Watling, 2015; Goncu-Berk, Karacan, & Balkis, 2022). 3D printing on decorative textile fashion products is significantly affected by printing speed, nozzle Z-distance, textile fabric

thickness, and deposited strand height (Kechagias, Chaidas, & Spahiu, 2024). According to Koziar, Blachowicz, and Ehrmann (2020), combining textile fabrics with three-dimensional printed components offers a cost- and time-efficient alternative to producing large-scale objects solely through additive manufacturing. This hybrid approach enables the tailoring of position-dependent mechanical properties for both design and technological applications. The principal challenge in such bi-material systems, however, lies in achieving robust adhesion between the composite partners.

Initial experiments by Grimmelsmann, Martens, Schäl, Meissner, and Ehrmann (2016) using 3D-printed objects as contact points between textiles or textile-integrated circuit paths and small electronic components demonstrated the suitability of this approach for establishing both electrical and mechanical connections. While the contact resistance between 3D-printed conductive materials and conductive wires or yarns can be reduced to acceptable levels, the interface between 3D-printed structures and subsequently inserted electronic components remains unsatisfactory. To address this limitation, integrating loops of the base conductive textile material directly into the 3D-printed objects offers a promising strategy. Experiments by Fajardo, Farez, and Paltán (2022) showed that elements structured in a linked-fabric pattern had a significant effect on the design of 3D-printed structured fabric and its tensile strength. In an all-cellulose approach, Tenhunen et al. (2018) observed that two tested cellulose derivatives attracted cellulose structures, but rigid cellulose had higher adhesion properties with higher affinity, while the more branched structure of flexible acetoxypopyl cellulose (APC) had lower affinity and adhesion properties. Using 3D printing of cellulosic materials for textile modification with higher functionalities eliminates labour-intensive processing or external glues, allowing new and simple customisation processes with minimised material usage.

Using two different polymers printed on cotton - polylactic acid (PLA) and polyamide 6.6 (Nylon) - across six cotton fabrics differing in structure, weight, and thickness, Gorlachova and Mahltig (2021) found that the best results are obtained at elevated process temperatures, intermediate printing speed, and low Z-distance between printing head and substrate. A textile pre-treatment by washing and desizing improved the adhesion of a subsequently applied 3D print. Results obtained by Goncu-Berk, Karacan, and Balkis (2022) showed that thermoplastic polyurethane (TPU) filament is compatible with all textile surfaces tested, and that neoprene exhibited the best adhesion with all filament types both before and after washing. By carefully adjusting the printing-nozzle height above a nanofibre mat, Koziar, Al Mamun, Sabantina, and Ehrmann (2019) achieved successful deposition on raw polyacrylonitrile (PAN) nanofibre mats, as well as on stabilised and even on the more brittle carbonised variants. Under these optimised conditions, adhesion between the two composite components is sufficiently strong to prevent delamination, abrasion testing reveals markedly enhanced mechanical performance, and contact-angle measurements show a hydrophilicity that lies between the intrinsic values of the electrospun and 3D-printed materials.

Recent advances in ceramic Additive Manufacturing (AM) highlight a shift toward high-precision, multi-material, and large-scale fabrication, moving beyond traditional limitations in geometric complexity and material waste. Researchers such as Chaput (2015) and Hwa, Rajoo, Noor, Ahmad, and Uday (2017) have contributed significantly to the development of slurry-based and photopolymerisation methods that improve the mechanical integrity and resolution of printed ceramic parts. A literature review by Sivaraman, Bharathiraja, Ahamadu, and Ramkumar (2025) noted that ceramic materials are widely used due to their desirable thermal, mechanical, and electrical properties, although these processes still require improvement in testing methods, raw-

material quality, cost efficiency, and material handling. In another review, Li, Peng, and Mu (2025) observed that ceramic additive manufacturing inherits the general principles of additive manufacturing but encounters greater challenges due to the high melting temperatures and intrinsic brittleness of ceramics compared to polymers and metals. Despite these difficulties, ceramics offer outstanding performance characteristics, and advances in additive manufacturing now enable the production of complex ceramic components with shorter lead times and reduced costs while preserving the qualities associated with conventionally manufactured parts.

At present, the fabrication of ceramics using AM techniques is constrained primarily by two limitations: low density and inadequate mechanical properties of the finished components. Current research is largely focused on overcoming these challenges by developing ceramic and cermet parts with enhanced densification and improved mechanical performance, although the systematic correlation between microstructure and mechanical properties has received limited attention (Saha & Mallik, 2025). In a further review, Gonzalez-Gutierrez et al. (2018) noted that, among the many variants of AM, material extrusion is the most commonly used. In material extrusion AM (MEAM), molten or viscous materials are pushed through an orifice and selectively deposited as strands to form stacked layers and ultimately a three-dimensional object. The commonly used materials for MEAM are thermoplastic polymers and particulate composites; however, innovative formulations of highly-filled polymers (HP) with metals or ceramics have become available. With HP, MEAM becomes an indirect process using sacrificial polymeric binders to shape metallic and ceramic components, after which the binder is removed and the powder particles fused in a conventional sintering step.

Digital craftsmanship theory explores the synthesis of traditional, hand-based making with computational tools, digital fabrication, and algorithms. It posits that digital tools - such as CNC milling, 3D printing, and robotic fabrication - are not merely replacements for manual labour, but extensions of the artisan's hand and mind. This emerging field reinterprets traditional knowledge, enabling the creation of unique, complex, and customised objects while retaining material sensitivity and human authorship; it is therefore inherently linked to both traditional knowledge and computational practice. Pop-Cohuț (2026) defined the concept of a “hybrid artisan” - one who strategically integrates AI-based design tools with traditional craft. From a review of 33 papers, the author identified three dominant human–AI collaboration models: task-level cooperation, process-level coordination, and system-level co-creation. LoRA-fine-tuned diffusion models and GANs achieve cultural-authenticity scores ranging from 73 to 95 per cent, while reducing design time by 30 to 70 per cent. Yet, empirical findings reveal notable paradoxes: artisans strongly value authentic creativity and sustainability (with 30.8 per cent rating sustainability as “extremely important”), but remain cautious in adopting AI, with 46.2 per cent unfamiliar with AI tools. Among those who do employ AI, reported productivity gains of 15 to 40 per cent have not translated into proportional increases in sales, suggesting that markets do not yet fully recognise or reward AI-assisted craft practices. The emerging hybrid-artisan model demonstrates greater success when AI is positioned collaboratively rather than autonomously, supported by explicit cultural safeguards in system design and transparent communication with consumers regarding AI involvement.

The possible connection between traditional crafts and computational tools was further discussed by Edet (2025). Based on three case studies, Varisco, Ponzoni, and Suls (2025) showed that the involvement of analogue techniques such as pattern drafting and sewing - alongside fashion-design knowledge and skills fostered through participatory engagement with study collections - remains central to practice. Equally significant are the characteristics of “digital

craftsmanship,” a method in which digital objects are meticulously shaped and refined in detail. Artefact digitisation also plays a pivotal role in advancing fashion research, particularly through approaches that seek not to replace object-based and material inquiry but to complement it; by enabling interoperability of digital files, this method opens multiple pathways for interpretation and expands the possibilities for engaging with fashion sources. From a mixed-methods study, Song (2022) observed that external variables of social influence and facilitating conditions are as important as personal motivations for craftspeople’s acceptance of technology, that technology has not yet progressed adequately to meet craftspeople’s expectations, and that traditional craft skills must be understood in order to take full advantage of these technologies.

Strategic Drivers for Digital Innovation

The interest in exploring AM as a complementary production technology is driven by three converging factors. First, the National Transformation Programme and Vision 2030 explicitly identify advanced manufacturing, cultural heritage, and the religious-tourism economy as priority sectors; investment in technologies that enhance the sustainability and reproducibility of sacred artefacts aligns with these national strategic priorities. Second, the global trend toward computational and parametric design in Islamic architectural and decorative practice - particularly the work on digital mashrabiya production reviewed by Almerbati and colleagues (2014, 2016) - has demonstrated that digital craftsmanship can preserve and even extend traditional aesthetic vocabularies rather than displacing them. Third, the broader sustainability agenda within the textile industry, particularly concerns regarding the environmental footprint of metallic-thread production and the energy intensity of traditional gilding processes, makes the case for exploring lower-impact alternatives that retain visual fidelity.

Theoretical Foundations

Digital Craftsmanship and the Preservation of Tradition

A central theoretical concern in any proposal to introduce digital manufacturing into a sacred craft tradition is the relationship between artisanal knowledge and computational reproduction. The position adopted in this paper, following Almerbati and colleagues, is that traditional craft knowledge is not necessarily lost when a process is digitised; rather, it can be preserved and made explicit by being encoded into the parameters that govern digital fabrication. Under this view, the role of the master craftsman shifts from direct manual execution to the curation, parameterisation, and validation of digital workflows. The aesthetic intelligence of the tradition is transferred from the hand to the algorithm, but it is not extinguished.

This position is normatively consequential for the present framework. It implies that the success criteria for an AM-produced Kiswah ornament are not exhausted by physical and visual specifications, but must also include the question of whether the parameterised digital workflow faithfully encodes the design intent of the traditional masters. A digitised letterform that meets dimensional and chromatic specifications but loses the calligraphic ‘breath’ - the subtle thickening and tapering, the directional sheen of the couched thread - would fail this test even if it satisfied measurable performance criteria.

The SAFE Model and Its Adaptation

The SAFE model proposed by Almerbati and colleagues for evaluating additive manufacturing in heritage architectural contexts identifies four evaluative domains: Social drivers for production, Aesthetic and Affordability factors, Functionality, and Economic and Environmental considerations. While developed for the architectural mashrabiya, the SAFE model translates productively to the Kiswah context with two important adaptations. First, the social and religious dimensions in the Kiswah case are inseparable; what would be a ‘social

driver' in a secular architectural context becomes a sacred imperative in the context of the Kaaba, and must be elevated accordingly. Second, the functional dimension in the Kiswah case is dominated by environmental durability under a uniquely demanding outdoor climate, which warrants explicit decomposition into thermal, photic, hydric, and mechanical sub-criteria.

Sacred Materiality and Substitution

A further theoretical question concerns whether the substitution of synthetic or ceramic material for gold and silk is, in principle, compatible with the religious function of the Kiswah. Two observations support an affirmative answer in principle, while reserving judgment on specific applications. First, the historical record demonstrates that the Kiswah has been executed in a wide variety of materials and colours over its history, indicating that the sacred function does not adhere uniquely to any single material substrate. Second, the religious authority for sanctioning Kiswah production resides with the Custodian of the Two Holy Mosques and the relevant religious institutions; any innovation in materials or technique would proceed under their explicit approval. The framework presented here, therefore, treats religious legitimacy not as a fixed external constraint but as a procedural requirement for stakeholder consultation and authorisation.

The Sacred Additive Manufacturing (Sam) Framework

The SAM framework proposed in this paper organises the evaluation of AM interventions in Kiswah production around four interlocking domains. Each domain is articulated through a set of explicit criteria, and the framework as a whole is designed to support both go/no-go decisions and comparative evaluation among candidate technical approaches. The four domains are summarised in Table 1 and elaborated in the subsections that follow.

Domain	Principle	Representative Criteria
D1. Sacred and Cultural Fidelity	Preservation of religious and aesthetic legitimacy	Approval by religious authorities; calligraphic accuracy of letterforms; tactile depth and relief; consistency with thuluth conventions; visual continuity with prior Kiswahs.
D2. Material and Environmental Performance	Durability under Makkah climatic conditions for one Hijri year	UV stability; thermal stability up to 80 °C surface temperature; resistance to hydric cycling; abrasion resistance; colour retention; substrate adhesion to silk.
D3. Production Economics and Sustainability	Reduced cost, waste, and labour intensity without compromising quality	Cost per square metre of finished ornamentation; production lead time; raw-material waste rate; embodied energy; end-of-life recyclability.
D4. Hybrid Craft-Digital Workflow	Integration with existing artisanal practice and labour pool	Role definition for master craftsmen; training requirements; parametric encoding of design knowledge; quality-assurance protocols; reversibility of digital interventions.

Table 1. The Sacred Additive Manufacturing (SAM) framework: domains, principles, and representative criteria.

Domain 1: Sacred and Cultural Fidelity

The first and overriding domain of the framework concerns the religious and cultural legitimacy of any proposed intervention. Three criteria operationalise this domain. The first is institutional approval: any departure from established Kiswah production practice requires the explicit endorsement of the Presidency for the Affairs of the Two Holy Mosques and consultation with relevant religious scholarship. The second is calligraphic fidelity: the letterforms produced by AM must conform to the established conventions of thuluth script as practised in Kiswah work, including correct proportional relationships, baseline conventions, and the characteristic curvilinear modulation of stroke width. The third is tactile and optical authenticity: the relief depth (approximately 20 millimetres) and directional sheen of the traditional couched gold thread are perceptual signatures that contribute meaningfully to the aesthetic experience of the Kiswah, and must be reproduced rather than merely approximated. A candidate technology that fails any of these three criteria is excluded from further consideration regardless of its performance on other domains.

Domain 2: Material and Environmental Performance

The second domain addresses the physical durability of AM-produced ornamentation under the specific environmental conditions of the Kaaba. The Kiswah is replaced annually, which establishes a one-year design life as the minimum acceptable benchmark. Within this period the ornament is subjected to ultraviolet exposure approaching 30 megajoules per square metre over the warmest months, surface temperatures that may exceed 70 degrees Celsius on the black ground fabric, episodic rainfall and significant overnight humidity swings, and incidental mechanical contact. Performance criteria within this domain accordingly include: ultraviolet stability quantified as colour retention (ΔE) after accelerated weathering equivalent to twelve months' exposure; thermal stability across a service range of 0 to 80 degrees Celsius without warping, embrittlement, or detachment from the silk substrate; hydric stability under cycling between 20 and 95 per cent relative humidity; abrasion resistance equivalent to or exceeding traditional couched gold thread; and substrate adhesion sufficient to withstand the vibration and air movement experienced when the Kiswah is suspended from the Kaaba structure.

Domain 3: Production Economics and Sustainability

The third domain addresses the economic and environmental rationale for adopting AM. While cost reduction is among the motivating drivers, the framework treats economic performance as a necessary but not sufficient condition. Criteria include: total cost per square metre of finished ornamentation, including materials, labour, and equipment amortisation; production lead time relative to the established eight to twelve month traditional cycle; raw-material waste rate, exploiting the near-net-shape capability of AM to reduce the offcut and trimming losses inherent in traditional embroidery; embodied energy of the production process, including any post-processing such as metallisation or curing; and end-of-life considerations, including the recyclability of polymer and ceramic substrates. Sustainability in this domain is understood broadly to include not only environmental footprint but also the long-term viability of the craft sector, recognising that wholesale replacement of artisanal labour with capital equipment would itself be a sustainability concern.

Domain 4: Hybrid Craft–Digital Workflow

The fourth domain articulates the conditions under which AM may be integrated with rather than substituted for traditional artisanal practice. The framework's position is that wholesale replacement of hand embroidery by AM is neither necessary nor desirable; rather, AM should be deployed selectively in those stages of production where its strengths - repeatability, geometric

precision, and reduced labour intensity - yield clear advantages, while artisanal skill is retained for those stages where human judgment, finishing quality, and the symbolic value of hand work are paramount. Criteria within this domain include: clear definition of which production steps are digitised and which remain artisanal; training and re-skilling pathways for existing Kiswah Factory craftsmen toward roles in digital workflow management; parametric encoding of master craftsmen's design knowledge into the digital pipeline; quality-assurance protocols at the interface between digital and manual stages; and the reversibility of digital interventions, such that any future decision to revert to fully traditional production is not foreclosed.

Application of the Framework: Candidate Technologies

The SAM framework can be applied prospectively to evaluate candidate AM technologies and material classes for Kiswah ornamentation. This section applies the framework to three principal candidates identified through preliminary review of the literature and informal consultation with practitioners: filled photopolymer resins processed by stereolithography (SLA) or digital light processing (DLP); metal-filled thermoplastics (PLA, PETG, or nylon) processed by fused deposition modelling (FDM); and technical ceramics processed by paste extrusion or vat photopolymerisation followed by sintering.

Filled Photopolymer Resins (SLA/DLP)

Photopolymer resins loaded with gold-coloured pigments or metallic-flake fillers offer high dimensional fidelity (layer thicknesses of 25 to 100 micrometres) and excellent surface finish, both of which are favourable for calligraphic detail (Domain 1). However, unmodified photopolymers exhibit known vulnerability to ultraviolet degradation, which is a critical concern for outdoor sacred use (Domain 2). Recent UV-stabilised resin formulations and post-cure surface treatments may mitigate this concern, but require empirical validation under Makkah conditions. Substrate adhesion to silk is not native to SLA processes and would require a secondary bonding stage. Production economics favour SLA for short runs, but the per-unit material cost remains higher than thermoplastic alternatives (Domain 3). Workflow integration is feasible (Domain 4), since resin-printing equipment is well-established and operator training is relatively short.

Metal-Filled Thermoplastics (FDM)

Thermoplastic filaments loaded with metal powders or pigments - particularly gold-look PLA, brass-filled PLA, and metallic-finish PETG - are widely available and economical. The literature on direct deposition of polymers onto textiles indicates that PLA in particular adheres well to woven fabrics, including cotton and synthetic blends, although direct evidence for adhesion to silk is limited. PLA is significantly more biodegradable and less prone to warping than ABS, but its thermal stability is constrained by a glass-transition temperature of approximately 60 degrees Celsius - below the recorded surface temperature of the black Kiswah in summer. This is a critical concern for Domain 2. PETG and nylon offer improved thermal performance and would warrant priority in empirical testing. The aesthetic question is whether metal-filled filaments can convincingly reproduce the directional sheen and depth of couched gold thread; preliminary inspection suggests that surface post-processing such as polishing or selective metallisation would be required (Domain 1).

Technical Ceramics

Ceramic materials processed by AM and subsequently sintered offer outstanding thermal and ultraviolet stability, making them strong candidates for Domain 2 criteria. Recent advances in ceramic AM, including loaded-resin formulations comprising approximately 80 per cent ceramic and 20 per cent resin, have substantially expanded the geometric and chromatic possibilities of

ceramic printing. Ceramics also accept a range of glazes that can produce metallic and lustre finishes consistent with the visual character of gold thread (Domain 1). The principal challenges lie in mass and adhesion: sintered ceramic ornaments would be substantially heavier than couched embroidery, potentially overloading the silk substrate, and the mechanical flexibility of the silk Kiswah is incompatible with rigid ceramic elements unless these are mounted on a flexible carrier. Ceramic AM also remains relatively energy-intensive (Domain 3) due to the sintering step. Despite these challenges, the durability advantages of ceramics warrant their inclusion among priority candidates for empirical investigation.

Figure 3. A complete ornamental panel from the Kiswah, showing the standard cartouche format used for shorter Qur'anic invocations. The interplay between the dense gold infill of the central script and the lighter outline of the surrounding floral cartouche illustrates the multi-density visual language that any AM substitute must reproduce. Source: Author's photographic record.

Roadmap for Empirical Validation

Application of the SAM framework to the three candidate technologies surveyed above identifies a structured programme of empirical work. The proposed roadmap comprises four phases.

Phase 1: Preliminary Material Screening (months 1–6)

Bench-scale printing of representative samples in each candidate material class, using a single standardised calligraphic test specimen. Initial characterisation of optical properties (colour coordinates, gloss, directional sheen), mechanical properties (flexural modulus, adhesion to silk substrate via lap-shear test), and indicative thermal stability.

Phase 2: Accelerated Weathering (months 5–14)

Exposure of down-selected materials to accelerated weathering chambers simulating one Hijri year of Makkah ultraviolet, thermal cycling, and humidity exposure. Periodic measurement of colour retention (ΔE), surface integrity (microscopy), and adhesion.

Phase 3: Field Exposure (months 8–20)

Outdoor mounting of surviving candidates on a test frame in Makkah, in parallel with traditional embroidered control specimens. Monthly visual assessment, quarterly instrumented measurement, and final post-exposure characterisation. This phase is critical because accelerated chamber testing does not fully reproduce the photochemistry of natural sunlight at low latitude.

Phase 4: Stakeholder Evaluation and Integration (months 18–24)

Structured presentation of surviving candidates to religious authorities, master craftsmen at the Kiswah Factory, and a sample of pilgrims, using mixed-methods evaluation against Domain 1 and Domain 4 criteria. Final framework refinement and recommendations for any pilot integration.

Discussion

The SAM framework presented here makes three contributions to the discussion of digital innovation in sacred craft. First, it explicitly elevates religious and cultural legitimacy to the status of a non-negotiable evaluative domain, in contrast to frameworks developed for secular heritage contexts where these considerations are typically subordinate. Second, it operationalises material performance through specific environmental parameters drawn from the Makkah microclimate rather than generic durability criteria. Third, it advances a hybrid model in which AM complements rather than displaces artisanal practice, addressing concerns about the loss of craft knowledge and labour displacement that have constrained the acceptance of digital methods in heritage sectors.

Several limitations of the framework should be acknowledged. The framework is primarily evaluative rather than generative: it can be used to assess proposed interventions but does not in itself prescribe specific technical solutions. The relative weighting of the four domains is left implicit, on the principle that any explicit weighting scheme would require negotiation with religious authorities rather than being determined unilaterally by researchers. The framework is calibrated to the Kiswah specifically and would require substantial adaptation for application to other sacred textile contexts. Finally, the framework does not address commercial governance questions concerning intellectual property, supply-chain control, and the role of foreign technology providers in sacred production - questions that, while important, lie outside the scope of the present paper.

Conclusion

This paper has presented the Sacred Additive Manufacturing (SAM) framework as a structured basis for evaluating the integration of additive manufacturing into the production of Kiswah ornamentation for the Holy Kaaba. The framework is grounded in four interlocking domains - sacred and cultural fidelity, material and environmental performance, production economics and sustainability, and hybrid craft–digital workflow - and provides explicit criteria within each. Application of the framework to three candidate technology classes identifies metal-filled thermoplastics, UV-stabilised photopolymer resins, and technical ceramics as warranting priority empirical investigation, and a four-phase research roadmap is proposed. The framework's central premise is that digital innovation in sacred craft contexts must satisfy not only technical and economic criteria but also religious legitimacy and the preservation of artisanal knowledge. The companion paper to this contribution presents the first phase of empirical validation against this framework.

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