CONCEPTUALISING AN ADDITIVE MANUFACTURING-ENABLED AGILE NEW PRODUCT DEVELOPMENT MODEL FOR ZERO-WASTE APPAREL MANUFACTURING IN SRI LANKA

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Abstract. As production volume expanded, the amount of pre-consumer textile waste generated globally by the apparel manufacturing industry increased dramatically. Because of this, the apparel manufacturing sector focuses on reducing waste in various ways. As a result, there are several opportunities to incorporate innovative technology and decrease textile waste in the apparel manufacturing process. By using precise, layer-by-layer production and faster product development, additive manufacturing helps reduce fabric waste and supports textile waste-reduction goals. This minimizes and eliminates waste that develops during the apparel manufacturing process. Among the many technological concepts spawned by the fourth industrial revolution (I4.0), additive manufacturing (AM) has emerged as a vital element of this new trend. The Sri Lankan apparel manufacturing industry is still in its early phases and has yet to implement AM technology, whereas industrialized nations have incorporated AM technology to reduce waste. This study investigates the use of additive manufacturing to reduce textile waste in Sri Lanka's apparel manufacturing sector, allowing for rapid agile new product development (NPD). To achieve this purpose, a thorough non-systematic review of the literature was conducted. The findings reveal that AM and agile NPD can be integrated in the apparel manufacturing process as a significant promise for driving a reduction in textile waste in apparel manufacturing. Accordingly, a conceptual model integrating AM and agile NPD was proposed as a key implication of this research.

Keywords. *Agile New Product Development, Additive Manufacturing, Apparel Manufacturing, Textile Waste, Zero-waste*

1. Introduction

The global apparel industry's rapid growth, driven by population increase and fast-fashion trends, has led to significant waste generation worldwide (Ütebay & Çay, 2020). Over the past few decades, the industry has more than doubled its production (Pitak & Sholokhova, 2025). The textile and apparel sector in Sri Lanka operates as an environmentally friendly and socially responsible supplier for major global brands. The industry experiences major value destruction because it discards textile waste materials (Kumarasena Samantha, 2025). Textile waste can mainly be categorized into three groups: production waste, pre-consumer waste, and post-consumer waste. According to Noman et al. (2013), the term textile waste refers to a variety of materials, such as fabric offcuts, polyester waste, cotton yarn waste, silk fibre waste, and so on. Globally, 73% of textile waste goes to incineration or deposition in landfills, and 12% is recycled, while only 1% of textile waste finds a second use. In fact, the recycling of textile-based products lags much behind the recycling of products fashioned from other materials. Where 15%-20% of textile materials undergo recycling, 80% of steel, 65% of paper, and 30% of plastics are processed for reuse (Ütebay & Çay, 2020). These numbers demonstrate that the majority of waste management strategies used today are still post-process treatment rather than process-integrated solutions. In response to industrial inefficiencies, the fourth industrial revolution (I4.0) introduced many advanced digital manufacturing

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technologies, and Additive Manufacturing (AM) has been widely recognized as a transformative approach (Villafranca et al., 2026). Additive Manufacturing (AM) is a process of creating three-dimensional objects by adding material layer by layer based on a digital 3D model, and it is commonly referred to as 3D printing (Omidvarkarjan et al., 2022). Although AM offers advantages such as design flexibility, customization, and waste reduction in sectors like aerospace, food industry, military sector, and healthcare, its adoption in sustainability-critical industries such as apparel remains limited. Its industrial adoption is constrained by material limitations, high costs, and infrastructural requirements (Montero et al., 2019).

Moreover, its application in sustainability-critical sectors such as apparel remains limited. Similarly, more flexible and iterative methods have replaced conventional linear models in New Product Development (NPD). Nonetheless, a large portion of the current NPD literature still places more emphasis on small-step changes than on systemic change. Agile NPD, on the other hand, offers an iterative, dynamic, and customer-centred development methodology that improves cross-functional cooperation and responsiveness (Yousaf Khan et al., 2024).

While the software and electronics industries have made extensive use of Agile principles, their use in physical production, such as apparel, remains underdeveloped and fragmented (Oye & Anthony, 2025). This demonstrates a gap between the industrial applicability of Agile in complicated production systems and its conceptual maturity. Recent studies suggest that the combination of AM with agile New Product Development (ANPD)helps designers to speed up manufacturing and iteratively reduce development time (De Almeida et al., 2021a). However, the majority of these studies focus on engineering-based industries like metalworking, paying less attention to the industrial contexts of textiles and apparel. Thus, how AM-enabled Agile NPD might be modified to meet sustainability issues, such as in apparel production systems, is not sufficiently explained by current research.

The Sri Lankan apparel industry holds a global position as a sustainable apparel manufacturer in the region (Sulochani et al., 2021). AM integration into Sri Lanka's apparel sector opens up many opportunities for tackling waste management and strategic interventions, including policy support, research and development investments, and capacity-building actions in the industry that are critical for overcoming existing barriers. Moreover, according to De Almeida et al. (2021), research specifically intends to assist managers and researchers in developing new products with AM technologies using agile approaches in the metalworking industry. It may be capable of delivering results faster to the market and closer to customer needs (De Almeida et al., 2021b). The underlying principles of transparency and customer feedback in Agile product development enhance the design for the AM process significantly (Montero et al., 2019). However, not much work has been done to integrate AM technologies into the Agile NPD processes in the context of apparel manufacturing, especially in developing countries such as Sri Lanka. Other than that, Additive Manufacturing (AM) application in apparel is still new, and although the potential increase in waste reduction, customisation, and shortening production cycles in other industries has been realised, it has yet to be realised by the apparel industry (Gamage et al., 2025).

Thus, a clear gap in the research is present in researching ways that combine these technologies in addressing specific issues, such as textile waste. Consequently, the purpose of this research is to develop an Additive Manufacturing (AM)-enabled Agile New Product Development (NPD) model for reducing textile waste in the apparel industry in Sri Lanka. Accordingly, this paper is limited to presenting its conceptual model addressing the main question of "How to reduce textile waste in the apparel industry in Sri Lanka through Additive Manufacturing (AM)-enabled Agile New Product Development (NPD)?"

Therefore, this research aims at conceptualising an Additive Manufacturing (AM)-enabled Agile New Product Development (NPD) model for zero-waste apparel manufacturing in Sri Lanka. Accordingly, two objectives were formulated:

(i) To explore the synergies of the integration of AM technologies into the Agile NPD process in the apparel industry,

(ii) To conceptualise an Additive Manufacturing (AM)-enabled Agile New Product Development (NPD) model for zero-waste apparel manufacturing in Sri Lanka.

2. Literature Review

2.1. TEXTILE WASTE MANAGEMENT IN THE APPAREL INDUSTRY

The apparel industry generates waste at multiple stages: fibre production, fabric manufacturing, garment designing, cutting, sewing, and distribution. Textile waste refers to any fibre, yarn, fabric, or textile material that has been discarded in the production and processing phases before the complete manufacture of a garment (final product). Textile waste management represents a systematic approach designed to reduce, reuse, recycle, and dispose of any waste, including pre-consumer, consumer, and post-consumer waste, that may be generated during the life cycle of textiles (Ütebay & Çay, 2020). According to Gupta & Kaur Saini (2020), research on textile wastes is divided into three categories. Such as pre-consumer (production), post-consumer, and industrial waste (Gupta & Kaur Saini, 2020). Pre-consumer wastes largely consist of cutting scraps, rejected fabrics, off-cuts, and defective garments produced during manufacturing (Noman et al., 2013; Pitak & Sholokhova, 2025). By contrast, post-consumer waste refers to discarded apparel items that have completed the life cycle of usefulness (Seifali Abbas-Abadi et al., 2025).

In Sri Lanka, significant pre-consumer waste is indirectly generated by the apparel industry, mainly due to high export-oriented production and design experimentation, which consequently has a significant bearing on the economic development of Sri Lanka (Edirisinghe et al., 2024). As an example, according to the Edirisinghe et al. (2022) in Sri Lanka, fabric and yarn waste dominate the textile waste stream at 4082.6 t/year, while contaminated fabric accounts for only 38.9 t/year; evidence from the Biyagama Export Processing Zone case study further confirms that fabric and yarn waste constitute the most prevalent waste type in apparel manufacturing, highlighting that material utilization inefficiencies are the primary drivers of waste generation in the sector. Furthermore, Kumarasena (2025) showed that one group of companies created 1900 tons of textile waste, while another company produced 80 to 200 tons of woven waste, 15 to 60 tons of knit waste, and 30 to 100 tons of shredded fabric waste each month. The third company declared its annual fabric waste at about 1375 tons. For environmental reasons alone, it is essential to solve the waste issue; however, it is also significant from the point of view of industrial competitiveness and corporate sustainability. Fashion value chains present how a garment goes through sourcing raw materials, designing, and production into distribution, usage, and disposal after its life ends or recycling. Historically, only landfilling and incineration have been used, both of which are detrimental to the environment, in the textile sector (Butturi et al., 2025). According to Park et al. (2019), Sri Lanka imported 294,000 tons of textiles in 2014 to support its apparel manufacturing operations. The process generates waste through fabric discarding at a rate between 15% to 20%, which results in a minimum production of 44,100 tons of textile waste before consumption. Landfills occupy good land and release methane gas, while incineration pollutes the air and releases harmful carbon. However, contemporary textile waste management approaches embrace the 3R (Reduce, Reuse, Recycle) and 5R (Refuse, Reduce, Reuse, Repurpose, Recycle) principles backed up by technologies of green manufacture and circular economy (Edirisinghe et al., 2024). It is possible to reduce waste in textile processing processes, particularly wet processing, as well as in the apparel sector. According to Kumarasena (2025), the National Policy on Waste Management NPWM establishes waste management procedures, yet it does not contain instructions for resource recycling and textile waste disposal methods. Local authorities face implementation problems that stem from missing sectoral policies and action plans, thus hindering their ability to execute environmental policies. This situation creates obstacles for sustainable textile waste management in Sri Lanka.

Technologies that are more environmentally friendly can be utilized to prepare textiles instead of chemicals (Gupta & Kaur Saini, 2020). Zero-waste production can be achieved by substituting modern technologies, such as large-scale 3D printing of clothing, for outdated cut-and-sew methods. Figure 1 below illustrates the apparel production flow and highlights key stages where waste occurs, along with potential interventions through Agile New Product Development and Additive Manufacturing (AM).

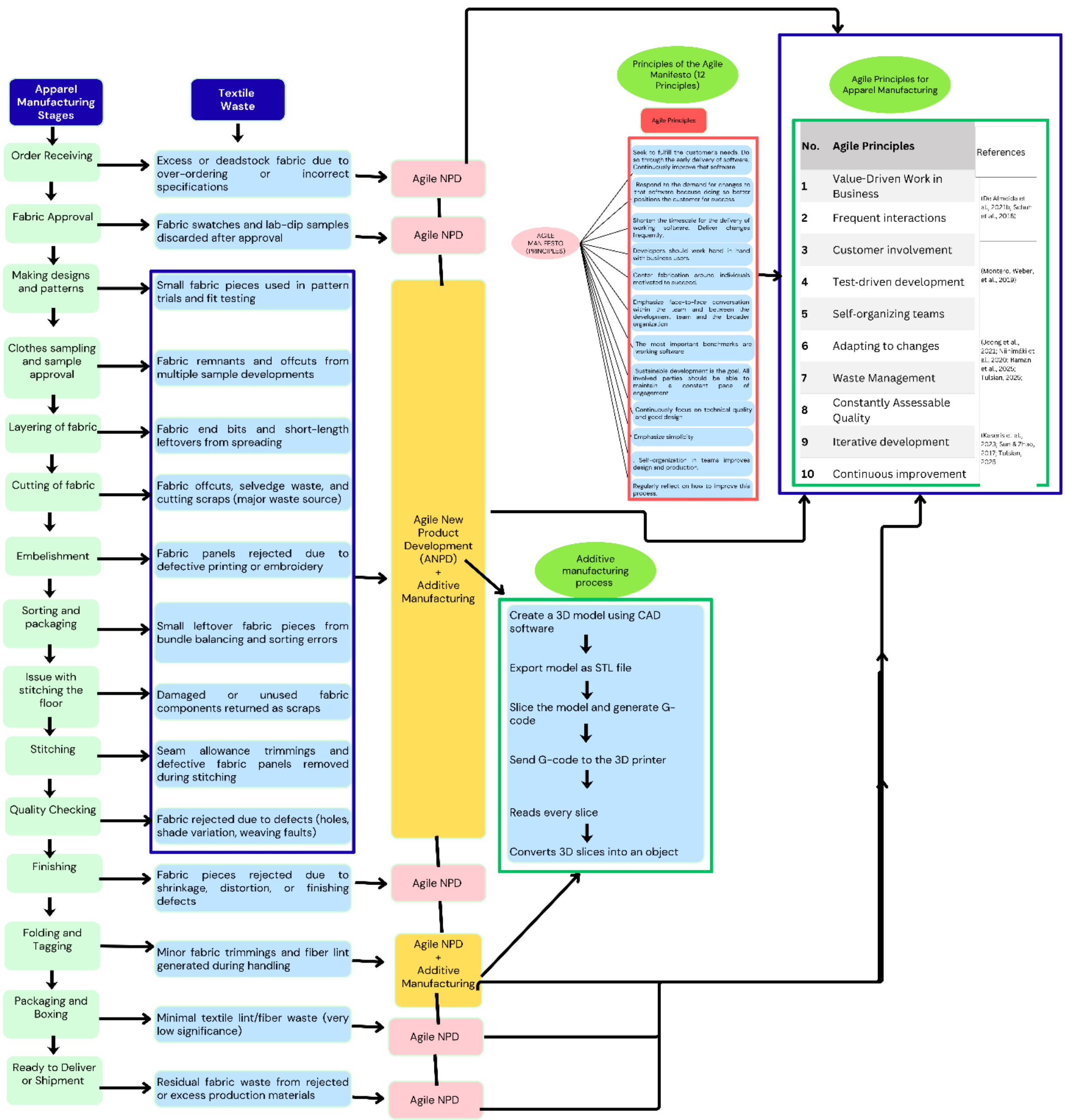

Figure 1, Apparel Production Flow with Waste and Agile–AM Interventions

2.2. THE CONCEPT OF AGILE NEW PRODUCT DEVELOPMENT

New product development (NPD) is becoming increasingly uncertain and volatile due to rapid technology advancements and shifting market demands (Thiele et al., 2020). To stay competitive, companies must produce new goods with more customer value more quickly than before (Salvato et al., 2020). These core issues in NPD have the potential for growth to be addressed by agile development methodologies. Fekri et al. (2009) and Moerth-Teo et al. (2021) stated that agile works along the route of sustainability by eliminating excess production, curbing material wastage, and encouraging precise manufacturing when emphasizing short, iterative development cycles. According to Leite & Braz (2016), agile manufacturing, as a concept, is essentially unknown worldwide and is not yet a common management philosophy for organizations, as it is flexible, cooperative, and responsive; an adaptive, iterative process (Leite & Braz, 2016). To enhance the software development process, a 17-member group of software developers created the Agile Manifesto in 2001 (Srirama Narasimha et al., 2025). Agile product development concepts were first developed with software development in consideration, but they are now being utilized in product management in a variety of industries, such as hardware, services, and even marketing (Srirama Narasimha et al., 2025). Furthermore, several case studies demonstrated that Agile techniques and technologies frequently require adaptation to handle the features of physical items (Omidvarkarjan et al., 2020). There are various perspectives on how to use agile approaches most effectively, such as Scrum, DSDM, and Kanban (Pisanu et al., 2025). Among the most crucial are the dynamic project management approach, Scrum, extreme project management, and adaptive project management. The Scrum general model is the most widely utilized of them (Fang, 2021). In a study by Suhartini et al. (2025), the agile NPD mathematical model for the development stage of the apparel industry has been proposed. The product studied is Muslim clothing. Furthermore, a mathematical model was developed, integrated with agile by Prabowo et al. (2020), and this research discusses the garment product development process, focusing on the planning stage and ideas to increase profits (Suhartini et al., 2025).

2.3. THE CONCEPT OF ADDITIVE MANUFACTURING

Additive manufacturing (AM), widely referred to as 3D printing, is mainly used for rapid prototyping (Montero, Weber, et al., 2019). Additive manufacturing, which creates objects layer by layer directly from digital models, allows for unprecedented, highly complex shape design flexibility and customization (Urbaite, 2024), further altering how products are visualized and manufactured (S. Khan et al., 2025; S. J. Khan et al., 2026). According to Attaran (2017), additive manufacturing currently makes it possible to produce moderate to large volumes of individually customizable products efficiently. AM has made practical achievements in many important industries (Banihashemi et al., 2025). AM is evolving into a radically disruptive technology in the closer interface of design and production in apparel (Attaran, 2017). As per the Khajavi (2021) study, the process's additive nature, reduced water use and greenhouse gas production, improved health, safety, and human capital development were highlighted as the general advantages of AM deployment in the apparel industry. Applications so far include the 3D printing of shoe soles, accessories, and experimental clothes (Idrees et al., 2024). The advent of several printer types has enabled AM to work with a variety of materials, including metals, ceramics, and polymers (Salonika & Marko, 2022). Several types of material printing, such as fused deposition modelling (FDM), stereolithography (SLA), selective laser melting (SLM), and electron beam melting (EBM), can be accomplished with 3D printing technology (Salonika & Marko, 2022).

3. Research Methodology

The type of research greatly influences the research methodology (Baharein & Noor, 2008). According to Manuel et al. (2020), systematic and non-systematic reviews are the two categories of literature reviews. Nonetheless, the research question that directs this study is: "How can an Agile New Product Development (NPD) model supported by Additive Manufacturing (AM) be developed to accomplish zero-waste apparel manufacturing in Sri Lanka?" In order to help waste reduction in the apparel industry, the study develops a conceptual framework that combines Agile NPD principles with AM. A qualitative and exploratory research approach is thought to be the most suitable since the goal of the study is to investigate, analyse, and construct linkages between these developing approaches rather than test quantifiable factors. This method makes it possible to have a thorough understanding of how AM-enabled Agile NPD can be set up to achieve zero-waste goals in the context of Sri Lankan apparel manufacturing (Celo et al., 2008). Therefore, non-systematic examination of the literature served as the methodological foundation for the current research. It refers to a review of previous research that is not carried out utilizing a rigorous, predetermined, and transparent approach for choosing and evaluating papers, and these reviews are commonly referred to as narrative reviews in academic literature. Finding, synthesizing, and summarizing a set of published literature while examining any potential research gaps are the goals of non-systematic reviews (Ferrari, 2015). Cunha Castro Alexandre Augusto Bezerra Da (2026) stated that the non-systematic reviews of the status of certain study areas from a theoretical and conceptual perspective are important for academic background.

Accordingly, in the literature, Google Scholar was selected as the main search tool because it provides access to a wide range of academic research materials across different fields. This literature conducted a search using keywords that matched the study area, which included the terms "Additive Manufacturing" OR "3D Printing" AND "Agile Product Development" OR "Agile Manufacturing" AND "Textile Waste" OR "Apparel Waste" AND "Waste Reduction" OR "Sustainable Manufacturing." This used the keywords to search through article titles, abstracts, and keywords in order to obtain all relevant study results.

The search produced a large collection of research materials, which contained both journal articles, conference proceedings, and review papers. This study review process involves examining the title and abstract of each study to determine its suitability for the research goals. The literature included peer-reviewed English-language journal articles and conference papers that examined additive manufacturing, agile NPD, and textile and apparel waste in research. This examined both early and recent studies from 2007 to 2026, which documented the development of additive manufacturing technologies and the evolution of agile practices.

4. Data Analysis and Findings

This section presents the key literature findings related to two major areas: (i) applications of agile NPD and additive manufacturing in the apparel industry, (ii) an additive manufacturing-enabled agile new product development model for reducing textile waste in the apparel industry.

4.1 APPLICATIONS OF AGILE NPD AND ADDITIVE MANUFACTURING IN THE APPAREL INDUSTRY

One theoretical method examined the features and applications of 3D printing technology, applying it to the fashion design process in a study that combined the two fields. According to Sun & Zhao (2017), who concentrated on digital production techniques utilizing 3D printing, they offered a theoretical model relevant to the fashion industry. Research on designing with 3D printing technology includes works on creating 3D-printed fabric structures by applying different geometric modelling concepts (Kim et al., 2019) as well as a study that focused on fashion accessory production (Dhiwar et al., 2024). Moreover, Jeong et al. (2021) discussed ABS (Acrylonitrile Butadiene Styrene) filaments were employed for strong structural design aspects because of their precise and buildable quality, while flexible TPU filaments were used for design features that require flexible and finer details. An FDM (Fused Deposition Modelling)-type 3D printer from HyVISION System called the "Cubicon Single" was utilized in this investigation. Rhinoceros 5, a 3D graphics application, and Grasshopper, a visual programming tool for Rhinoceros, were used to create the patterns. The measurements of the 3D CAD model for printing were created and modified using Cubicreator. However, new techniques for integrating 3D printing into various apparel may be developed in future research (Jeong et al., 2021). TPU and ABS filament to produce a variety of fashion items, such as clothing and accessories. This was a reaction to the results of earlier studies that successfully produced bags, shoes, and clothes (Jeong et al., 2021; Kim et al., 2019). Table 1 demonstrates the most widely used materials and current technologies in FDM technology. The most widely used materials and current additive manufacturing technologies (Elena Stroe & Maria Aileni, 2022).

Table 1, Additive manufacturing technologies and used materials

Category	**Type / Method**	**Key Materials**	**Bonding Principle**
Resin-based	Material Jetting (PolyJet)	Photopolymers, polymers, waxes	Cured with UV light
Powder-based	SLS (Powder Bed Fusion)	Plastic, metal, ceramic powders, sand	Fused with a laser
Filament-based / Material Extrusion	FDM (Fused Deposition Modelling)	Thermoplastic filaments, liquids, slurries	Fused with heat
FDM Material Examples	PLA (Polylactic acid)	Polylactic acid (biodegradable polymer)	Extruded at ~215°C
	ABS (Acrylonitrile Butadiene Styrene)	Acrylonitrile Butadiene Styrene	Extruded at ~220°C
	Nylon	Polyamide	Extruded at 240–270°C

	TPU (Thermoplastic polyurethane)	Thermoplastic polyurethane	Extruded at ~230°C
	PC (Polycarbonate)	Polycarbonate	Extruded at ~315°C

Technology support that offers the flexibility of capacity and speed of production and prototyping is required for the set of technologies and systems (Leite & Braz, 2016). Agile manufacturing emerged as a result of the knowledge gained from the experience of earlier philosophies, presuming that the notion is multifaceted and that it cannot be fully isolated from management philosophies that were previously in use (Bremer et al., 2025).

Identified agile principles in the apparel manufacturing are Value-Driven Work in Business, Frequent interactions, Customer involvement, Test-driven development, and Self-organizing teams, Adapting to changes, Waste Management, Constantly Assessable Quality, Iterative development, and Continuous improvement (Montero, Weber, et al., 2019; Thenuwara & Sandanayake, 2018). Table 2 demonstrates the application of Additive Manufacturing (AM)-enabled Agile New Product Development across different stages of the apparel manufacturing process.

Table 2: Application of AM technology enabled agile new product development in the apparel manufacturing process

Stage of apparel process	**Additive manufacturing process**	**Agile principles**	**Application of AM to the apparel manufacturing process**	**References**
Making Designs & Patterns	1. Create a 3D model using CAD software	value-Driven Work in Business	A 3D printed sample is produced by 3D CAD design software.	
Clothes Sampling & Sample Approval	2. Export model as STL file	Frequent interactions		
Layering of Fabric	3. Slice the model and generate G-code	Customer involvement	Combining the processes of cutting, stitching, laying, and	(De Almeida et al., 2021b; Schuh et al., 2018)
Cutting of Fabric	4. Send G-code to the 3D printer	Test-driven development		(Montero, Weber, et al., 2019)

Sorting & Packaging (Pre-stitch)	5. Reads every slice	Self-organizing teams	fabric assembly into a single step	(Jeong et al., 2021; Niinimäki et al., 2020; Raman et al., 2025; Tulsian, 2025;
Issues with Stitching Floor (Pre-Stitching)	6. Converts 3D slices into an object	Adapting to changes		(Kaseris et al., 2023; Sun & Zhao, 2017; Tulsian, 2025
Stitching		Waste Management		
Quality Checking		Iterative development		
Folding & Tagging		Continuous improvement		
Packaging & Boxing		Constantly Assessable Quality		
Ready to Deliver / Shipment		Value-Driven Work in Business		

4.2 AN ADDITIVE MANUFACTURING-ENABLED AGILE NEW PRODUCT DEVELOPMENT MODEL FOR REDUCING TEXTILE WASTE IN THE APPAREL INDUSTRY

A conceptual framework that offers significant insights for future studies in the field was developed based on the evaluation of how additive manufacturing enables agile new product development in the apparel industry to reduce textile waste. In order to facilitate agile new product development for the apparel industry, the framework provides clear illustrations of the apparel manufacturing process, the application of additive manufacturing, and agile new product development. Additionally, the framework demonstrates the connections between the various phases of the manufacturing process for apparel, as well as the uses of agile new product development and additive manufacturing.

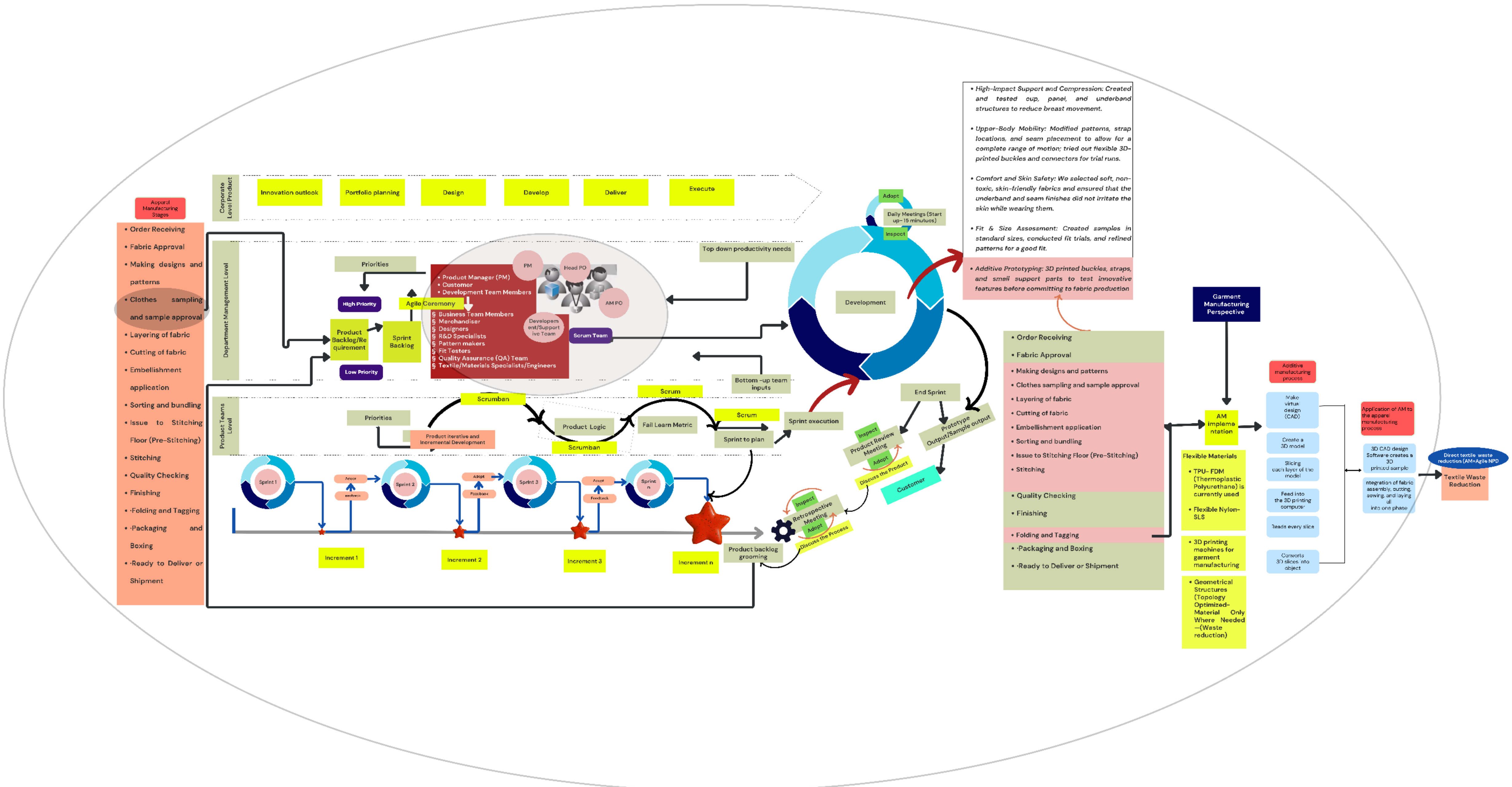

Figure 2, The conceptual framework

5. Discussion

In the present time, additive manufacturing has proven to be beneficial in the case of replacing damaged parts, without requiring any proven certification (Omidvarkarjan et al., 2023; Villafranca et al., 2026). The production of spares using this metallic Additive Manufacturing (AM) stems from military research, but really has far-reaching application and relevance to many other industries, especially now that Industry 4.0 is emerging (Montero et al., 2019). The process complexity and uncertainties, however, make the principles of agile hardware development a practical approach to obtaining flexibility, speed, and adaptability (Coates, 2007). According to Pisanu et al. (2025), despite significant advancements, the design process still has to be improved in order to facilitate large-scale mass manufacturing and further assist the development of AM technologies. Stakeholder participation in departmental operations and educational programs is an important strategy to raise awareness of AM solutions and make them more appealing to decision-makers (Eyers et al., 2018).

AM enables the fast, low-waste prototyping and small-batch sampling, which complements agile iterative sprints and cross-functional collaborative work, particularly where digital PLM and 3D design are established; that is, it works in early local pilots using 3D-printed parts, samples from 3D knitting, and digital prototyping. Given buyers' sustainability expectations and ongoing sector digitalization, the outlook is positive, contingent on scaling successful pilots, aligning incentives, and building a supporting ecosystem for technology adoption and agile governance (De Fonseka, 2023; Thenuwara & Sandanayake, 2018). According to Alwis & De Silva (2022), additive manufacturing can reduce human error and be easily adjusted to meet needs. It is able to smooth demand variations and speed up the process of manufacturing. If 3D printing were applied, there would be a huge reduction in apparel manufacturing faults. Even though the printouts that were attached were sufficiently flexible to communicate the organic fluidity of parametric design, the garment was noticeably heavier due to the high density of the filament (Kim et al., 2019). For future designs, a lighter and more flexible 3D printing material should be available to increase the practicality of fashion items (Jeong et al., 2021).

6. Conclusions and a Way Forward

The adoption of additive manufacturing enables agile new product development, offering a transformative opportunity to reduce textile waste in Sri Lanka's apparel manufacturing industry. The adoption of additive manufacturing and agile new product development helps to achieve sustainability goals, including waste management in the apparel industry. The evidence of this research highlights the tremendous potential of AM and agile NPD in areas that have high fidelity, the ability to produce complex geometries, manufacturing flexibility, and reducing material wastage.

These attributes support industry sustainability objectives and provide an innovative way of reducing waste and optimising resources. However, to enable the effective implementation of AM, there are major barriers to be addressed, such as the high costs of machines and materials, limited availability of raw materials, lack of design competency, and the issue of certain AM materials being non-recyclable. Conversely, the use of AM can greatly improve the current waste management practices in the apparel sector in Sri Lanka through the adoption of agile NPD practices. The strategic interventions, which include policy support, research and development funding, and industry capacity building, must be implemented to overcome these obstacles. Future research should investigate sustainable material innovations and scalable examples of AM used custom to the apparel sector's requirements. With such a necessity, the conceptualised AM-enabled agile NPD model will be applied in a real manufacturing industrial context for appropriate context-specific enhancements. Sri Lanka can become a leader in sustainable apparel production through its use of AM-enabled agile new product development technologies, which create more environmentally friendly and resource-efficient manufacturing processes.

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