ADDITIVE MANUFACTURING FOR ZERO WASTE APPAREL MANUFACTURING INDUSTRY IN SRI LANKA: A LITERATURE REVIEW

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Abstract. Global pre consumer apparel waste generation in the apparel manufacturing industry drastically increased with the rise of production volume. Therefore, the apparel manufacturing industry focuses on different ways to minimise waste, and the zero waste concept is one of the main concepts regarding waste elimination. However, the achievement of the zero waste concept remains challenging and traditional waste elimination techniques or methods are outgrown to achieve the zero waste concept within the current context. Accordingly, integration of novel technologies shows considerable opportunities to achieve zero waste concepts. AM contributes to zero waste goals by enabling precise material deposition and eliminating cutting waste, which minimises as well as eliminates waste occurring in the apparel manufacturing process. The fourth industrial revolution (I4.0) introduced many technological concepts, and Additive Manufacturing (AM) has been identified as an integral part of this new trend. While developed countries integrate AM technology into their apparel manufacturing industries for waste reduction, Sri Lanka's apparel manufacturing industry remains in its infant stage of adoption, and there is no adoption of AM technology in the apparel manufacturing industry. Thus, this study focuses on investigating the adoption of additive manufacturing concepts for the apparel manufacturing industry in Sri Lanka to achieve zero waste goals. To achieve this research aim, an extensive non-systematic literature review was conducted, synthesising insights from existing scholarly works. The findings indicate that while additive manufacturing presents significant potential for advancing zero-waste apparel production, several barriers must be addressed to facilitate its successful implementation. The findings of this study reveal that there are some potential as well as barriers in adopting additive manufacturing for zero-waste apparel manufacturing in Sri Lanka. High fidelity, realisation of complex structures, property predictability, flexibility of manufacturing, improving sustainability, minimum manufacturing footprint and on-demand manufacturing are some remarkable potentials of additive manufacturing. Accordingly, these attributes position AM as a promising solution for minimizing waste in the apparel industry. In contrast, machine and material cost, raw material availability, insufficient design knowledge and non-recyclable nature are some of the identified potential barriers. In conclusion, further research and strategic interventions are recommended to overcome these challenges and facilitate the sustainable integration of AM technologies in the industry.

Keywords. Additive Manufacturing (AM), Apparel Manufacturing, Pre-Consumer Apparel Waste, Zero Waste

1. Introduction

Globally, the apparel manufacturing industry has a significant production capacity, and consequently, it produces an immense quantity of solid waste (Nadeera et al., 2022). Further, Choudhury (2014) claimed that the apparel industry ranks as one of the top polluting industries in a global context. Islam et al., (2022) stated that the environmental impact of the textile and apparel industries extends across all the stages of the manufacturing process. Population growth, lifestyle advancements, and the progression of the global apparel manufacturing industry over the recent decades have been affected by the considerable increase in apparel waste production (Chand et al. 2023). However, with the emerging trend of sustainable development concepts, most textile industries focus on creating a suitable waste management system as part of the sustainable journey (Nadeera et al., 2022).

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Hence, there is a growing interest in employing innovative concepts, such as circular economy and zero waste to address the waste issue (Zaman, 2022). According to Nizar et al. (2018), zero waste aims to minimise waste, reduce landfills, and protect the environment. Further, Kerdlap et al. (2019), illustrate that both future production growth and waste reduction can be addressed with a zero-waste manufacturing (ZWM) strategy that takes a comprehensive approach to life cycle management. Nevertheless, Dilberoglu et al. (2017) claimed that Industry 4.0 emphasises the significance of the integration of advanced information technology and smart manufacturing systems, and additive manufacturing (AM) has been identified as an integral part of this new trend. Further, Hegab et al. (2023) illustrate that AM technology reduces material waste, CO2 emissions, and promotes the circular economy, it is recognised as environmentally sustainable.

When heeding the Sri Lankan textile and apparel industry, it takes pride in being a global leader in sustainable clothing manufacture in the region (Sulochani et al., 2021). According to Park and Evans (2017), the apparel sector is Sri Lanka's largest manufacturing sector, accounting for 61% of exports and 44% of GDP in 2015. Gunasekara et al. (2019) stated that waste management has emerged as a significant problem in modern society that requires investigation, particularly in Sri Lanka's apparel manufacturing industry. As a result, introducing proper waste management procedures is becoming increasingly crucial.

Even though, there is a significant gap in Sri Lanka's manufacturing sector in implementing Industry 4.0 for such environmental implications (A. M. L. De Alwis et al., 2023). Furthermore, Jayatilake and Withanaarachchi (2016) highlighted that Sri Lanka’s leading apparel manufacturers are yet to converge on Industry 4.0 concepts such as additive manufacturing to tackle the waste management challenges and to move towards zero waste. Thus, it will be beneficial to focus on achieving zero waste goals of the apparel industry through additive manufacturing technology. Accordingly, this research paper aims to review the adoptability of the additive manufacturing concept to achieve zero waste goals of the apparel manufacturing industry in Sri Lanka as a way forward for future research.

In order to achieve the research aim, two (02) research objectives were formulated;

- To explore on apparel waste generation and management, the zero-waste concept, and additive manufacturing
- To identify the potentials & barriers and future trends of additive manufacturing for achieving the zero-waste concept in the apparel manufacturing industry.

Accordingly, the next chapter describes the apparel waste generation and management, the zero-waste concept in the apparel manufacturing industry and the concept of AM. The third chapter will discuss the research methodology that has been adopted for this study, and the fourth chapter will discuss the findings on the application of AM, barriers, and potentials for adopting AM in the apparel industry.

2. Literature review

This section presents the key literature findings related to three major areas; (i) Apparel waste generation and management, (ii) Zero waste concept in the apparel manufacturing industry, and (iii) The concept of additive manufacturing.

2.1. APPAREL WASTE GENERATION AND MANAGEMENT

The generation of waste in the garment industry is one of the inevitable elements of garment manufacturing (Rathinamoorthy, 2018). Apparel waste is defined in different terms, such as textile or clothing as well as fabric or garment waste by scholars. Textile waste refers to materials that cannot be used for their intended purpose, originating from the apparel and textile industries (Redress, 2017). According to Noman et al. (2013), the term "textile waste" refers to a variety of materials, such as clippings and cuttings, polyester waste, cotton, clippings, 100% cotton yarn waste, silk fibre waste, etc. Accordingly, in this research apparel waste is defined as "materials that cannot be used for their intended purpose, which are originated from the manufacturing process of apparel industry".

The two categories of apparel waste are pre-consumer waste and post-consumer waste, depending on where the waste originated. (Tomovska et al., 2017). Vadicherla and Saravanan (2014) mentioned that pre-consumer waste are formed during the production process of upstream items, whereas post-consumer apparel wastes are generated by customers and frequently consist of apparel acceptable for landfill or disposal. Redress (2017) identified textile swatch waste, cut and sew textile waste, end-of-roll textile waste, sampling yardage waste, damaged textile waste, clothing sample waste, and unsold clothing waste as pre-consumer waste. In contrast, post-consumer waste includes secondhand clothing waste and secondhand textile waste. Alternatively, according to Shakya & Swami (2016), apparel waste generation in the production stage is pre-consumer apparel waste and they are related to pattern making, marker planning, and cutting as well as the post-consumer apparel waste generated in the consumption stage.

Alwis and De Sliva (2022), identified the apparel manufacturing process under fourteen stages; order receiving, fabric approval, design/ pattern making, garment sampling and sample approval, fabric layering, fabric cutting, sorting and bunding, issue to stitching floor, garment stitching using machines, quality checking, finishing and complete, folding and tagging, packing and boxing and ready to deliver or shipment. Further, according to Amin (2020), a considerable quantity of waste is produced throughout the process of the product development process, especially in the fabric loss and cutting departments of the apparel industries. As Redress (2017) mentioned, pre consumer apparel waste generated sources and types of waste such as the production process – textile swatches, garment manufacturing process - cut and sew waste, and end of rolls waste, textile sample process – sampling yardage, design process – clothing samples, finishing – damaged textile, and unsold clothing waste. When heeding the apparel waste management strategies, present waste management procedures are heavily impacted by the "waste hierarchy," which suggests a ranking of options in order of preference, with "prevention" being the most favoured at the top and "disposal" being the least liked at the bottom (Gharfalkar et al., 2015). Ajila (2019) claimed that apparel and textile wastes can also be managed using the 4R method which includes reduce, replace, reuse, and recycle. Further, the Concept of Circular

Economy has been applied to pre-consumer apparel waste management using lean manufacturing, green supply chain management, extended producer responsibility, and the 3R concept (Jayakodi & Thayaparan, 2021). However, nowadays "zero waste" strategy is often utilised to eliminate textile waste in the apparel manufacturing process (Italiano et al., 2022).

2.2. ZERO WASTE CONCEPT IN THE APPAREL MANUFACTURING INDUSTRY

Hamid et al. (2020) claimed that zero waste management refers to a holistic approach to waste management that recognises waste as a resource produced during the formative stage of the resource consumption process. Further, according to the Pietzsch et al. (2017), zero-waste approach focuses specifically on reducing the amount of waste created, has emerged because of the development of the circular economy concept. The goal of zero-waste fashion designing is to completely remove fabric waste from the manufacturing of clothing. (Shakya & Swami, 2016).

Gupta and Saini (2020) stated that there are several strategies for achieving zero waste concept as jigsaw cutting, subtraction cutting, geo-cut, cutting and draping, re using scarps of clothes and yarns, knitting, pleating, draping scraps of fabric, replacing conventional technology with no/low waste technology like additive manufacturing. AM is one type of digital manufacturing technology that has a good influence on the environment and reduces manufacturing errors (Ott et al., 2019). Developing and implementing new and more effective manufacturing techniques, including additive manufacturing, reduces raw material use and fosters innovation for sustainability (Todeschini et al., 2017).

3. Methodology

The research approach for any research strongly depends on the nature of that research (Baharein & Noor, 2008; Morgan & Smircich, 1980). However, this research works out on the research question of "how to adopt the additive manufacturing concept to achieve zero-waste goals of the apparel manufacturing industry in Sri Lanka" which represents the findings through a theoretical framework. Since this research focuses on investigating the areas mentioned above by answering the "How" question, the qualitative research approach is more favoured for this research. In addition to that, Celo et al., (2008) stated that quantitative research entails converting phenomena into numerical values for analysis while qualitative research deals with non-numerical data forms such as texts, pictures, videos, and so on. However, since this research involves only qualitative data rather than numerical data, the qualitative approach is the most appropriate for this research. Accordingly, a non-systematic review of the literature was used as the methodological basis to complete the present study. According to the enferm (2007) , the two types of literature reviews are systematic reviews and non-systematic reviews. Further, it mentioned that non-systematic reviews are commonly referred to as narrative reviews in academic literature. Non-systematic reviews aim to identify, synthesise and summarise the existing published literature while exploring the potential research gaps for future research (Ferrari, 2015). Further enferm (2007), claimed that non-systematic reviews state of science on a particular research area from a theoretical and conceptual perspective and play a vital role in academic background.

Accordingly, a non-systematic literature review was conducted to identify the key literature publications in the intersection of apparel waste generation and management, additive manufacturing and zero waste concepts.. The articles were retrieved through the Google Scholar search engine and included suitable original articles and reviews written in English. The Search string was developed using the following keywords: additive manufacturing, zero waste in apparel industry, sustainable apparel manufacturing, circular apparel production, and sustainable textile production. Consequently, the literature synthesis was developed analysing the selected publications.

4. Results

This section presents the key literature findings related to three major areas; (i) The concept of additive manufacturing (ii) Applications of additive manufacturing in the apparel industry, (iii) Potentials and barriers to adopting additive manufacturing concept in the apparel manufacturing industry.

4.1 THE CONCEPT OF ADDITIVE MANUFACTURING

According to Dehghani and Goyal (2022), additive manufacturing involves creating a virtual design of an object using a 3D modeling application or a 3D scanner. The 3D printer then reads each slice, creating a three-dimensional object, which is referred to as polymer to a garment. Process of 3D printing shown in figure 1.

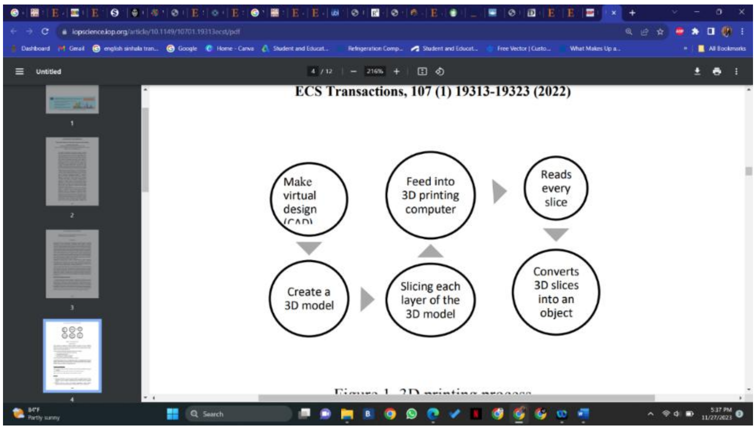

Figure 1: Process of 3D Printing

3D CAD design software is where the process of creating a 3D printed sample begins (Partsch et al., 2015). In order to begin the 3D printing process, users must first design things using a 3D modelling program or select from an online database, then upload them to slicing software. After all settings are finished connect the printer to the computer and start printing (Trust & Maloy, 2017). According to Ligon et al. (2017), additive manufacturing processes are utilised for different materials, including material extrusion, material jetting, binder jetting, sheet lamination, vat photopolymerisation, powder bed fusion, and directed energy deposition. Ngo et al. (2018b) stated that AM used Fused Deposition Modelling (FDM), powder additive manufacturing by Selective Laser Sintering (SLS), Selective Laser Melting (SLM) or Liquid Bonding in 3D printing (3DP) as well as Inkjet Printing, Contouring, Stereolithography (SLA), Direct Energy Deposition (DED) and Manufacturing of Laminated objects (LOM). Alafaghani et al. (2017) stated that AM process of fused deposition modelling (FDM) involves heating and extruding filaments through a tiny nozzle to create objects. The nozzle uses computer-controlled pathways to extrude the material, forming layers on top of one another to form the part. According to Shahzad et al. (2013), SLS is an additive manufacturing technique that produces parts layer by layer using layers of powder deposited by a roller or scraper and heated by a laser beam. The powder deposition and laser scanning sequence is repeated until the part is finished. According to Miller et al. (2023), in SLA, layers of three-dimensional parts are selectively cured using UV photopolymer resin. This process produces parts that require minimal applied stress, which makes it possible to create detailed features and complex geometries. Saboori et al. (2019) claimed that among AM processes, DED enables the restoration of damaged parts to their original shape as well as the replacement of materials lost during service. According to the Gupta et al. (2020), one type of AM process that uses sheet lamination to create 3D solid objects is called LOM.

4.2 APPLICATIONS OF ADDITIVE MANUFACTURING IN THE APPAREL INDUSTRY

AM is an innovative emerging technology that is used for several purposes across multiple disciplines due to sustainability perspectives (Niaki et al., 2019). Further, (Khajavi, 2021; Keefe et al., 2022) also emphasised the ability to offer sustainable innovation and customisation in the apparel industry. According to the Harsha Vardhan et al. (2014), industries which are benefiting from additive manufacturing technology are, aerospace, automotive, machine tool production, healthcare and medical, dentistry and dental technology, architecture and construction, food, retail, and apparel. Additive manufacturing has numerous benefits for future space flight (Shapiro et al., 2016). Vasco (2021) mentioned that the freedom capacity of AM enables the design and direct manufacturing of automotive components optimised for vehicle performance, along with the creation of assembly tools required to increase productivity. Furthermore, Leal et al. (2017) highlighted that the AM approach allows stamping inserts to be produced using high-performance alloy steels similar to conventional tools without losing the mechanical properties of the tool. The flexible manufacturing methods offered by AM are revolutionising the manufacturing of medical models, passive implants, biomanufacturing, orthoses prostheses, medical equipment, and instruments in the healthcare sector (Rezvani Ghomi et al., 2021). Moreover, according to Javaid and Haleem (2019), additive manufacturing is an innovative process that is leads to the customised fabrication of dental implants and other dental instruments with the help of computer-aided design (CAD) data. Additive manufacturing (AM) is a cutting-edge technology that provides new freedom in architecture with endless flexibility in material deposition and design, manufacture and performance of unique forms, construction systems and materials (Paoletti, 2017). Lipton et al. (2015) stated that main motivations for 3D printing food are customisation, on-demand manufacturing, and geometric complexity. Traditional foods like pizza using 3D printers could demonstrate the maturity of food printing.

Valtas and Sun (2016) highlighted that reduces the number of stages that must be completed during production. By creating a design, 3D printing allows for the integration of fabric assembly, cutting, sewing, and laying all into one phase and Because 3D printing eliminates the possibility of human error in traditional garment manufacturing, the product is of greater quality than when it was made. In the design process, AM offer greater capabilities for designing and customising apparel products (Yap and Yeong, 2014). Further, Am technologies such as 3D printing allows personal customised apparel products by integrating 3D scanning and CAD software in design process (Spahiu et al., 2020). When heeding the fabric layering process in apparel manufacturing, AM facilitate the layer-by-layer manufacturing process which eliminates the necessity for different cutting tools and machineries (Lim et al., 2016). Furthermore, Dilek et al. (2021) stated that in the application of AM technology to the apparel manufacturing process, stages such as spinning, dying, cutting, and sewing of the manufacturing process are not involved. Additionally, (Hohn and Durach, 2021) claimed that the implementation of AM helps to reinforce existing supply chain governance structures dominated by powerful retailers, potentially exacerbating social sustainability issues in production. According to the literature, it can summaries the application of AM technology to apparel manufacturing process as shown in table 1.

Table 1: Application of AM technology to the apparel manufacturing process

Stage of apparel manufacturing process	**Additive manufacturing process**	**Application of AM to the apparel manufacturing process**	**References**
Design / pattern making	1. Make virtual design (CAD) 2. Create a 3D model	3D CAD design software creates a 3D printed sample	(Valtas & Sun, 2016), (Verlan & Irovan, 2018), (Partsch et al., 2015), (Yap and Yeong, 2014)
Garment sampling and sample approval			
Fabric layering	3. Slicing each layer of the model	Integration of fabric assembly, cutting, sewing, and laying all into one phase	(A. M. L. D. Alwis & De Silva, 2022)(Lim et al., 2016)
Fabric cutting	4. Reads every slice 5. Feed into the 3D printing computer 6. Converts 3D slices into object		
Sorting and bundling			
Issue to stitching floor			
Garment stitching using machineries			

4.3 POTENTIALS AND BARRIERS TO ADOPTING ADDITIVE MANUFACTURING CONCEPT IN THE APPAREL MANUFACTURING INDUSTRY

Expansion of manufacturing methods and options due to additive manufacturing technologies offers significant benefits such as reductions in product lead time, shorter time to market for new designs and faster fulfilment of customer demands (Attaran, 2017). Notable benefits of additive manufacturing include less material waste, ease of manufacture with simplified manufacturing process, fewer requirements for human intervention and post-processing, and energy efficiency (Mansi et al., 2023). According to the Quan et al. (2015), potentials of additive manufacturing in apparel manufacturing industry are high fidelity, realisation of complex structures, and property predictability. Khajavi (2021) emphasised that

AM offers a highly flexible way to manufacture clothing parts and products, thereby improving sustainability and extending life cycles. This technology enables the production of complex geometries in small batches, allowing for efficient production, repair, and overhauls. Furthermore, reduction of need of the excessive transportation led to a lower environmental impact. Moreover, Keefe et al. (2022) further outlined potentials of AM over conventional apparel manufacturing methods, including ability to produce complex geometries, minimise waste, reduce transportation and CO2 footprints, wide range of materials, high-value replacement parts, small manufacturing footprint, green manufacturing, and on-demand manufacturing. However, barriers can be identified as limited raw materials, limited printing accuracy, requirement of powerful design tool (Seepersad, 2014). Khajavi (2021), further stated time-dependent barriers to using AM technology in the apparel industry include machine and material costs, raw material availability, automation, and brand support. Time-independent barriers involve insufficient design knowledge, lack of retail store experience, and insufficient enthusiasm for being involved in the production process. Additionally, Nath and Nilufar (2020), highlighted critical barriers of AM as difficulties in the mass manufacturing due to limited materials and its non-recyclable nature of certain AM materials, unsatisfactory level of surface quality in the printed product of some AM processes, and relatively low strength of printed parts. Although, as per the Withanaarachchi et al. (2016) main barriers in Sri Lanka can be identified as labour shortage, machine cost, and lack of enthusiasm within apparel manufacturers. Furthermore, Samarakkody (2023), claimed that barriers in implementing technologies like additive manufacturing in Industry 4.0 as financial barriers, insufficient knowledge, high maintenance cost etc.

5. The theoretical framework for adopting additive manufacturing in the apparel manufacturing industry to achieve zero waste

Based on the insights reviewed on adopting additive manufacturing in the apparel industry to achieve zero waste, a framework was developed providing important insights for future researchers in the field. The framework clearly illustrates the apparel manufacturing process, application of additive manufacturing, potentials & barriers and benefits of adopting additive manufacturing for the apparel industry. Further, the framework clearly illustrates the relationship among the different stages in the apparel manufacturing process and applications of additive manufacturing as well.

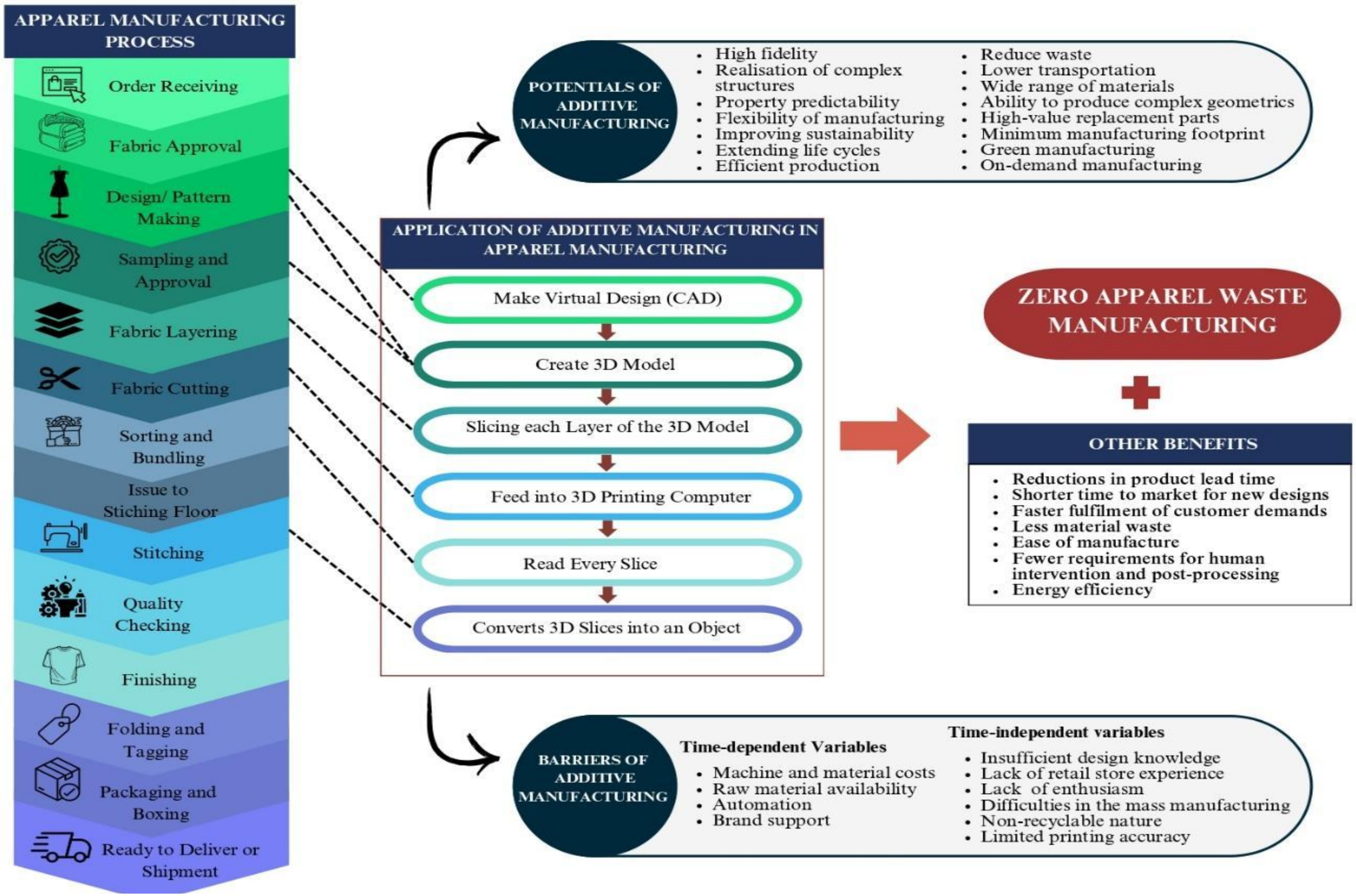

Figure 2: Theoretical framework for adopting additive manufacturing in the apparel manufacturing industry to achieve zero waste

6. Discussion

When heeding on Sri Lanka context, there is no any acceptable waste management system in Sri Lankan apparel manufacturing industry. Typically, only 25% of apparel waste is recycled and reused; the remaining waste is incinerated or landfilled (Jayakodi & Thayaparan, 2021). Nonetheless, waste has grown in significant issue in the current setting of Sri Lanka due to urbanisation and high human density. Edirisinghe et al. (2022) highlighted that fabric waste accounts for the majority of waste generated through Sri Lanka's apparel industry. Park and Evans (2017) mentioned that Sri Lanka generates at least 44,100 tons of textile waste annually, but lack of proper recycling facilities. As of currently, Sri Lanka lacks recycling facilities, and there are no established waste management initiatives. Basically, waste is moved out of cities and disposed in open spaces. Therefore, it is more beneficial for moving novel technologies such as additive manufacturing to overcome the waste issue and achieve zero waste goals in apparel industry.

As stated by different research scholars, Additive manufacturing is expected to become one of the most important and innovative industrial processes in the coming years (Jiménez et al., 2019). According to the Dilek et al. (2021), number of synthetic materials utilized in 3D printers is growing daily. Fashion designers are experimenting with 3D printed clothes, shoes, and accessories to introduce 3D printing to the apparel industry (Kholiya, 2016). The use of 3D printing for apparel manufacturing not only brings new advantages but also changes the entire production and design development of the product as well as the relationship with the customer (Marques, 2019). Verlan and Irovan (2018) claimed that since the model is created in a software that specifies the precise dimensions and form of the landmark, it is evident that use of AM to create apparel in an innovative way and helps to reduce the waste. An avatar can be built using the data from the body scan, enabling online testing and style, fit, and other verifications. This ensures that apparel is made to actual measurement (Grimmelsmann et al., 2016). Waste minimisation is one benefit of using 3D printing in manufacturing. Once printing is finished, there is nothing to trim away from the object because it is complete in it’s as a whole (Sun & Zhao, 2017). Designers and manufacturers have the option to print directly for customers, which minimises waste. Making a garment more functional through 3D printing could potentially prolong its lifespan from a sustainability standpoint (Pasricha & Greeninger, 2018). In the upcoming years, it is anticipated that natural materials will be developed. Wong and Hernandez (2012) revealed that continuous and incremental growth experienced since the early days and the successful results to date allow for optimism that additive manufacturing will have a significant place in the future of manufacturing. According to Alwis and De Silva (2022), the integration of Industry 4.0 and sustainable manufacturing in the context of Sri Lanka is not well-established. Although additive manufacturing is currently in discussion level. Withanaarachchi et al. (2016) mentioned that apparel manufacturing industry as a whole needs to reconsider the adoption of Industry 4.0 including AM as a new business model and the study also recommends that further research be done on the viability of installing smart factories and the implementation of Industry 4.0 in the apparel sector.

7. Conclusion and Way Forward

The adoption of additive manufacturing offers a transformative opportunity for achieving zero-waste goals in Sri Lanka’s apparel manufacturing industry. The adoption of additive manufacturing helps to achieve sustainability goals including waste management in apparel industry. Accordingly, this study demonstrates the significant potentials of AM, including high fidelity, the realization of complex structures, flexibility in manufacturing, and minimal material waste. These attributes align well with the industry's sustainability ambitions, offering an innovative approach to waste reduction and resource optimization. However, key barriers such as high machine and material costs, limited raw material availability, insufficient design expertise, and the non-recyclable nature of certain AM materials must be addressed to facilitate effective implementation.

Despite these challenges, the integration of AM into Sri Lanka's apparel sector can significantly enhance waste management efforts and contribute to a circular economy. Strategic interventions, including policy support, investment in research and development, and capacity building within the industry, are essential for overcoming existing barriers. Future research should explore sustainable material innovations and scalable AM applications tailored to the apparel sector's unique needs. By leveraging AM technologies, Sri Lanka can position itself as a leader in sustainable apparel manufacturing, paving the way for a more resource-efficient and environmentally responsible industry.

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