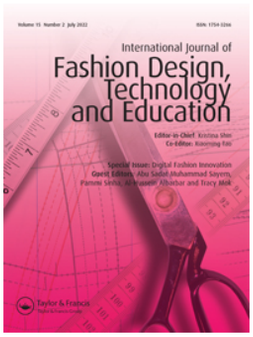

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A comparative review of zero-waste fashion design thinking and operational research on cutting and packing optimisation

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ABSTRACT

This paper provides a review aimed at comparing cutting and packing (C&P) research in the textile industry and the area of zero-waste fashion design (ZWFD). Both research domains seek to minimise waste material while approaching the problem from very different perspectives. The C&P research investigates the use of mathematical and computational techniques for minimising material waste in the marker planning problem, while the ZWFD provides creative pattern making solutions for the same problem. A systematic literature review was performed based on content and bibliometric analysis of 22 papers published in peer-reviewed journals from 2010 until 2021. The paper maps the research direction of both the C&P and ZWFD as an opportunity to stimulate further research in the future encouraged by the integration of both areas to address the zero-waste fashion designs' manufacturability problem by incorporating the fashion design process with the C&P optimisation algorithm design process.

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KEYWORDS
Zero-waste; fashion design; cutting and packing; marker planning problem; automated markers

1. Introduction

With the emergence of fast fashion and the increasing rates of fashion consumption, the fashion industry's business models shifted towards cost reduction methods and techniques while ignoring essential factors such as the environmental cost of the fashion industry (Niinimäki & Hassi, 2011). Fashion designers are beginning to challenge the system's linearity and seeking to prevent waste through the elimination of fabric waste during the cutting stage of garment manufacture.

This paper reviews two research paradigms dealing with eliminating fabric waste during the cutting stage of a garment. The first, Cutting and Packing (C&P) in the field of Operational Research (OR), develops computational methods for the cutting problem. The C&P research has contributed to the design of automated markers for software providers such as Lectra by using different optimisation algorithms and artificial intelligence to minimise fabric waste during the cutting stage.

The other research paradigm is the Zero-Waste Fashion Design (ZWFD) which challenged traditional fashion design principles to eliminate fabric waste to 0%. However, most developed methods achieved minimal waste rather than zero-waste due to the different variables affecting the design decision making process. Automated markers still do not utilise 100% of the fabric and are not designed to accommodate the zero-waste design practices, making it challenging for zero-waste designers to use available software as part of the design process and thus incorporate speed and efficiency as required by industry. The fabric waste generated in the cutting stage of fabric is estimated to be almost 15% of the total fabric used in manufacturing. Even though there are some efforts for waste management through the use of fabric leftover, the problem remains due to the mismatch between the investment required to manage fabric waste and the value of leftovers which can come at a cost to the manufacturer (WRAP, 2019).

To the best of our knowledge, no literature provides a connection between the C&P and the ZWFD research areas, even though both research areas aim to eliminate fabric waste. The relationship between both areas offers an opportunity for examining how to incorporate zero-waste fashion design principles into automated markers with the potential for industrial application. The review aims to integrate the knowledge from zero-waste fashion design research and the C&P research. This integration will allow future research in C&P to improve marker automation and provide a flexible system tailored to ZWFD thinking, not only traditional fashion design.

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2. Background

2.1. Operational research: cutting and packing optimisation

Operational Research (OR) is a quantitative scientific research field that utilises different analytical techniques and mathematical models to facilitate operational decision-making and problem-solving to complex managerial problems across a wide range of businesses and organisations in various sectors (Carter, Price, & Rabadi, 2018). The OR community tackles different system-level operational problems by developing models to inform strategic and operational decisions.

Cutting and packing (C&P) is an active research area in the OR community that addresses operational problems associated with the utilisation of space or material. In manufacturing industries that require cutting of materials such as textile, glass, leather, metal and ceramics, research focuses on computational methods for automated cutting plans to increase productivity and material efficiency. When targeting any operational problem, the OR approach begins with developing a precise articulation of the problem's characteristics, constraints, and objectives, which may require some assumptions or simplifications. As a result, a quite messy problem becomes closer to a puzzle.

One of the research applications in the C&P community is cutting textiles for garment manufacturing (see Figure 1), focused on tackling one of the most critical operations in the garment industry of marker planning. The research area focuses on developing algorithms to create marker layouts. In C&P, this problem is referred to as the nesting problem or marker planning problem, where irregular pattern pieces have to be placed on a strip of fabric such that there is no overlap between the pattern pieces and all pattern pieces are contained within the boundary of the strip (Wäscher, Haußner, & Schumann, 2007).

The markers or pattern pieces are often represented as irregularly shaped polygons; the fabric roll has a fixed width and is a long enough strip to contain all pattern pieces. To solve this problem, a decision procedure is constructed in the form of an optimisation algorithm designed to find the best possible solution based on the problem input and the specified objective, i.e. no overlap and containment.

Two key strands of research deal with the problem: the first is how to computationally model the geometric aspect of the problem so a computer can efficiently identify feasible arrangements of shapes; the second is how to create good layouts given the infinite number of possible configurations. The different computational geometry methods for the former are reviewed in Bennell and Oliveira (2008). For the latter, there is a wide range of search algorithms applied; see Bennell and Oliveira (2009).

Over the years, C&P research has seen methodological improvements and more powerful computers, which has improved marker automation. Even though the problem definition in C&P has many commonalities with real-world applications, there are also many lost opportunities due to some significant differences between how C&P researchers approach the fabric minimisation problem and how practitioners in the garment industry tackle the problem. Even though each industry has its problem specification based on the nature of the raw material used and other industrial constraints. The C&P community approach nesting problems from different industries with similar solution methods and approaches because the end goal is the same, which is to nest the pieces in the smallest space possible. To the best of our knowledge, papers covering the marker planning/nesting problems are rarely focused on specific industrial constraints and rarely challenge the static nature of the problem definition.

One of the main limitations facing operational research is ignoring the flexibility in the problem constraints. This pragmatism would require human intervention to adjust the shapes and orientation. Such that, in solving the marker planning problem, different solution methods and techniques are primarily based on trial and error. Techniques that provide good solutions can be adopted and expanded using more trial and error to find better solutions.

In this paper, we are reviewing different approaches to minimising the waste from the fashion designer's

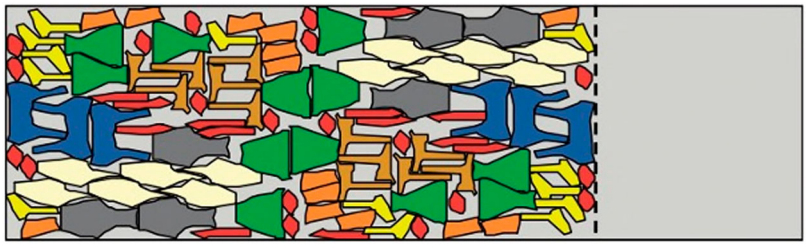


Figure 1. Marker layout example. (Bennell & Oliveira, 2008).

perspective, which might present an opportunity to expand on the future research in the C&P area and provide better solutions to the marker planning problem that integrates the fashion design thinking into the formulation of the solution. The following section introduces the other research paradigm tackling the marker planning problem from the garment design perspective.

2.2. Fashion design: zero-waste fashion design

Research in fashion sustainability posits that the leading cause of textile waste, specifically in the production stage of the garment, is the separation between the design and make processes. Designers conceptualise the garment design, and pattern makers create the patterns to be cut from a fabric roll in the most efficient way possible, which is still inefficient. Therefore, the design mainly dictates the amount of waste generated during the production stage of the garment.

Zero-Waste Fashion Design (ZWFD) emerged to challenge the sector's boundaries and the inefficiencies in the design/make process of garments. Zero-Waste Fashion Design Practices (ZWDP) are based on the idea that fabric and form are interconnected. The primary constraint when designing zero waste is to utilise 100% of the fabric width either through single or multiple garments (McQuillan, 2020b). The term zero-waste was first introduced in the fashion context by Fletcher (2008) to transform the whole fashion system and supply chain from farmers to consumers while considering the circular economy approach.

Zero-waste design is not a new concept and existed in different cultures even before industrialisation. Zero-waste clothing could eliminate cuts in the fabric or wraps the fabric length around the body, such as the sari in India. Also, it could be based on minimal cuts such as the kimono in Japan, which utilised folding, draping and geometrical cuts in garment construction. The inspiration behind those garment construction techniques was that we valued fabric differently. As C&P and zero/minimal waste pattern cutting are working separately to achieve the same goal of minimising fabric waste, we undertook a systematic literature review. It outlines the processes, activities, and design thinking involved in designing zero-waste or minimal waste garments and compared it with the C&P approaches to the marker planning problem and minimising cutting waste.

3. Literature review methodology

A research plan was developed to systematically review the relevant literature in the area of ZWFD and C&P in the textile industry (see Figure 2). Inclusion and exclusion criteria of the selected papers were developed based on the objectives of the research. First, to establish the grounding behind the importance of integrating both research areas through content and bibliometric analysis. Second, to explore different methods and techniques related to ZWFD and C&P optimisation in the textile industry. The authors chose to include peer-reviewed journal research papers published from 2010 to 2021, as this period witnessed growth in publications, specifically in the area of ZWFD.

The databases used for extraction for both areas are Web of Science, Scopus, Taylor & Frances, Springer Link, MDPI, Emerald Insight, and Science Direct. Other journals were included in the initial search, such as Clothing Textile Research and Fashion and textiles. However, we either did not find relevant papers to include in the review or found duplicates. In the initial search, we used logical operators and different synonyms of the keywords identified to ensure that we covered a broad range of papers in both research areas.

An initial search in the ZWFD area was carried out using keywords such as 'zero-waste', 'fashion design', 'sustainable fashion design', 'fashion design thinking', 'fashion system thinking', 'creative pattern cutting'. While for the C&P area, the initial search keywords were 'cutting and packing', 'textile industry', 'apparel industry', 'fashion industry', 'garment construction', 'fabric waste'. The search produced 595 papers for initial screening based on titles and abstracts. After the initial screening, 515 papers were excluded for the following reasons: papers beyond the scope of the work, including papers published on education, reuse/recycling, 3D printing, green/eco designs, and papers not specific to the methodological aspect of ZWFD practices and pattern cutting. Moreover, papers excluded from the C&P initial screening mainly were not specific to the fashion/textile industry. It is challenging to find papers in the C&P area that are curated to a specific industry; for this reason, the authors tried to use different variations of the keywords 'textile/apparel/fashion design'. As we mentioned before, the C&P research often focuses on the geometrical aspects of the problem, the shapes of the pattern pieces, rather than focusing on problems related to a specific industry.

From the 80 papers screened for full text review, we only included papers that specifically explore ZWFD different methods and papers in the C&P area specific to the textile industry for a journal overview of selected papers (see Figure 3). Moreover, we excluded papers unrelated to the topic, papers that didn't target problems related to the cutting problem in the fashion/textile industry and papers in languages other than English. After excluding 58, 16 papers in the ZWFD and 6 papers in C&P were considered in the review.

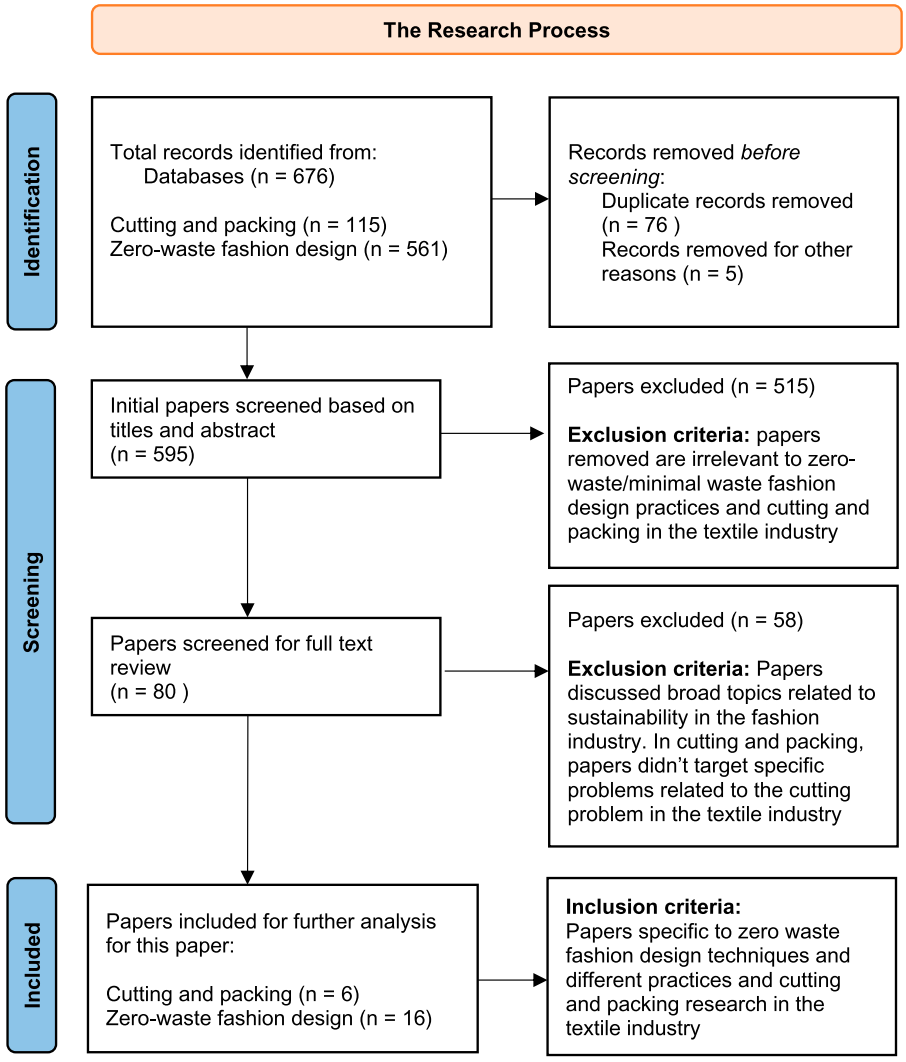


Figure 2. The research process flowchart.

4. Findings and discussion

Two key themes were identified in the zero-waste fashion design literature: *zero-waste fashion design technical knowledge; and zero-waste fashion industrial implications and support tools* (see Table 1). Those themes will be reviewed with minimal waste methods

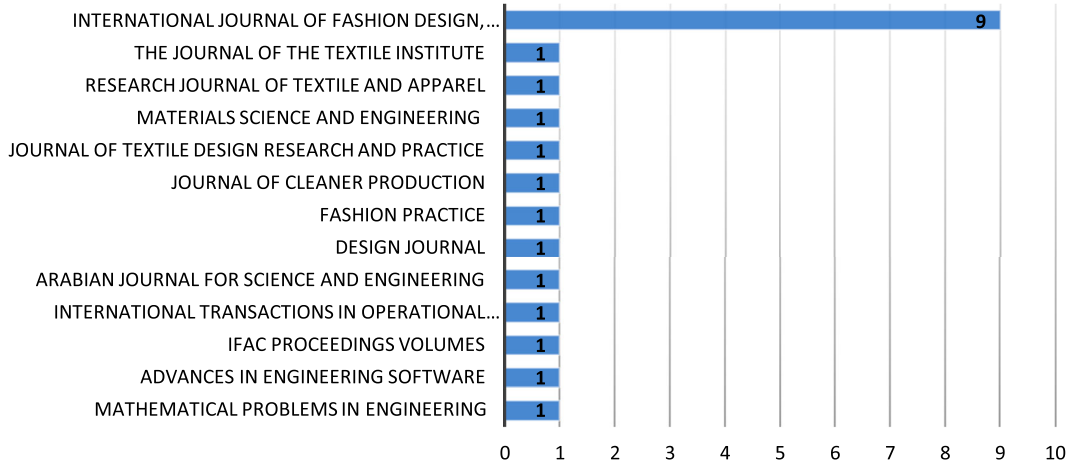


Figure 3. Overview of the research papers used in the literature review for the ZWFD and C&P papers by journal.

in the C&P literature to identify gaps and opportunities. The term 'zero-waste fashion design' has been referred to all approaches intended to eliminate fabric waste from a garment's cutting stage, even approaches that do not eliminate the waste completely (minimal waste). However, to align with the research in the literature, we will use the term 'zero-waste'.

4.1. Zero-waste fashion design: technical knowledge

The research in zero-waste fashion is almost entirely practice-based (Nelson, 2013), which assimilates practice in zero-waste design methodology to gain new experiential knowledge that helped widen the technical expertise in the zero-waste fashion paradigm (see a summary of the common methods Figure 4).

4.1.1. The development of zero-waste fashion design

The idea of a zero-waste fashion system has led designers to adopt 'precarious design', later known as 'ZWFD' as a way to mitigate textile waste and uncertainties through considering material and environment in the design process (McQuillan, 2009). Precarious design requires challenging the traditional approach to fashion design. A designer will develop his concept and sketches, then present them to a patternmaker who creates the appropriate pattern for manufacturing. However, designers like Roberts, Rissanen, McQuillan and Mark Liu realised that to develop zero-waste patterns, accepting uncertainties and risk into the design process is essential to the design process.

Before developing the term 'ZWFD', Rissanen (2005) investigated approaches that minimise textile waste, specifically jigsaw puzzle, which is based on cutting irregular shapes from fabric and trying to match the shapes to form a design. This approach allows for full utilisation of fabric through considering the design in both 2D jigsaw pattern and its ability to be translated into 3D form. Another designer who challenged the traditional design process is Julian Roberts (2008). He created a technique, 'subtraction cutting', based on manipulating negative space in the garment to create different shapes and designs where the concept of design is in the pattern cutting rather than the other way around.

With the idea of precarious design, the term 'zero-waste fashion design/construction methods' emerged influenced by established minimum fabric waste methods discussed earlier.

4.1.2. ZWFD technical knowledge: pattern cutting & making

Traditionally pattern cutting is treated as a distinct role from fashion design and operated by a specialist who is usually not involved in the design process. The separation between the role of fashion designers and pattern cutters was found to hinder opportunities to solve sustainability problems such as fabric waste (McQuillan, Rissanen, & Roberts, 2013). Motivated by this, sustainable fashion designers integrated pattern cutting and fashion design to create zero-waste designs. Pattern cutting became an essential part of the design process rather than merely an outcome of the design.

Additionally, ZWFD requires thinking outside the conventional ways by creating zero-waste garments that consider key design elements such as appearance, fit, cost, and manufacturability, making garments attractive for the industry and consumers (Rissanen & McQuillan, 2016).

Townsend and Mills (2013) suggested that regardless of the design process, identifying and evaluating successful steps at each stage is essential for the progression of the design, which requires having the appropriate experiential knowledge from trying different cutting approaches and techniques. The zero-waste design approach requires holistic knowledge and skills in pattern making, draping, design, and garment construction. Unlike traditional pattern making, in the zero-waste approach, any change in the construction of one piece will affect another. However, this is not always the case in traditional pattern making (Carrico & Kim, 2014).

In 2011, The Cutting Circle project showed that each designer had a different starting point to the design process despite having a common objective to create zero-waste garments (McQuillan et al., 2013). For instance, McQuillan usually starts developing a 2D pattern on computer software and works her way up by considering body and space until reaching a satisfactory design. Rissanen used pattern cutting and draping simultaneously, as well as sketching patterns and layout on a garment. Roberts used his method 'subtraction cutting', which involves using patterns as designs. Roberts has a unique design thinking that involves designing for the interior space of the garment rather than the exterior (McQuillan et al., 2013).

Carrico and Kim (2014) reviewed and analysed different zero-waste design approaches by McQuillan and Rissanen (2011): tessellation, jigsaw, embedded jigsaw, and multiple cloth technique, and provided solutions to problems in the techniques, as well as proposed a new approach called 'minimal cut'' based on draping as the primary method.

Table 1. Summary of the key themes and concepts from the ZWFD literature.

Years	Author	Themes and Key Concepts								
		Technical Knowledge							Zero/Minimal Waste Fashion Design Implications and Support Tools	
		Pattern cutting	Textile properties and fabric specification	Sizing and fit consideration	Marker planning/ digital marker planning	Design tools (CAD/ 3D software)/ 2D to 3D	Experimentations/ knowledge transfer	Other variations of zero/ minimal Waste Fashion Design techniques	Industrial Applications	Open source platforms
2013	**McQuillan, H. et al.**	×					×			
2013	**Townsend, K., & Mills, F.**	×	×				×			
2013	**Niinimäki, K.**						×			
2014	**Carrico, M., & Kim, V.**						×			
2016	**Rahman, O., & Gong, M.**							×		
2016	**McKinney et al.**	×								
2016	**Choi, K. H.**	×						×		
2016	**James, A. M. et al.**	×				×	×			
2018	**Saeidi, E., & Wimberley, V. S.**	×		×		×				
2018	**McQuillan, H. et al.**					×	×			×
2019	**McQuillan, H.**						×		×	
2020	**McQuillan, H.**					×			×	
2020	**Senanayake, R., & Gunasekara Hettiarachchige, V.**		×				×	×		
2020	**Scerbaka, A.**						×			×
2020	**Enes, E., & Kipöz, Ş.**		×		×				×	
2020	**Ramkalaon, S., & Sayem, A. S. M.**			×	×	×			×	

Zero-waste fashion design methods

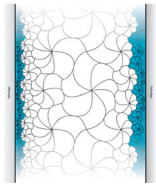
Concept	Method	Design	Main Designers
Creative pattern making	Embedded Jigsaw Designing pattern like puzzle pieces, the design is embedded within the length of the fabric	 (Holly McQuillan, 2011)	Timo Rissanen, Holly McQuillan
	Jigsaw Designers can build the design around a specific shape like a sleeve. Pieces are manipulated to interlock with each other and share the same cut edge	 (Mark Liu, 2016)	Holly McQuillan, Mark Liu
	Creative Cut Designers try to start their designs with a word like (peace in the figure) and build the pattern pieces around it	 (Rissanen & McQuillan, 2016)	Holly McQuillan
	Tessellation Patterns are repeated on a fabric in a decreasing order like fractals, then pieces are cut and manipulated into a design	 (Rissanen & McQuillan, 2016)	Holly McQuillan

Figure 4. Zero-waste fashion design methods. (Note: These are the methods discussed in the literature).

Tessellated patterns contain a shape repeated on the fabric without gaps. McQuillan's tessellation approach uses fractals where the shape's scale decreases as it gets closer to the edge of the fabric. Her approach was viewed as complicated and cannot be adopted in manufacturing since it requires overlapping pattern pieces that might be acceptable aesthetically but not commercially practical (Carrico & Kim, 2014). For this problem Carrico and Kim (2014) suggested to use shapes with straight edges so that it aligns with the grain of the fabric, another strategy would be to add other shapes to the tessellated pattern. Jigsaw and embedded jigsaw have been widely experimented with by practitioners(Carrico & Kim, 2014; McQuillan & Rissanen, 2011; Townsend & Mills, 2013). It manipulates different irregular shapes to interlock and share the same cut edges to create a zero-waste design. Another method is the multiple cloth technique which allows for different styles to be combined within the same marker using digital printing (Carrico & Kim, 2014; McQuillan & Rissanen, 2011).

Research in creative pattern cutting that does not focus on the concept of zero-waste has been an inspiration to zero-waste fashion designers. Choi (2016) researched experiential methods on how to use the origami folding technique as a way to create unique patterns. Moreover, understanding the underlying design

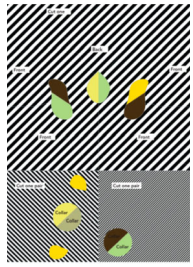
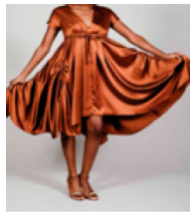
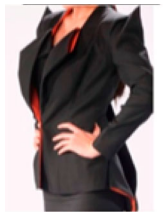
Draping	Subtraction Cut Design is based on the use of negative space (holes) in fabric to create a shape	 (Holly McQuillan, 2011)	Julian Roberts
	Minimum Cut Design is based on draping and allowing for minimum cuts in the fabric	 (Carrico & Kim, 2014)	Holly McQuillan, Melanie Carrico & Victoria Kim
Folding	Transformation reconstruction Design starts with style line drawn on a basic block, then turned into a flat pattern where space is manipulated by folding and draping	 (Shingo Sato, 2015)	Shingo Sato
	Origami Patterns are created through the folding technique of origami and then turned to a flat pattern to be cut and sewed	 (Choi, 2016)	Kyung-Hee Choi

Figure 4 *Continued*

methodology of other creative pattern cutting techniques such as 'deconstructionism' of garments through the use of knots and uneven hemlines, or 'Kimono' techniques based on draping, overlay, and wrapping around the body, can expand the designer's knowledge beyond the traditional realm of pattern cutting and design (Choi, 2016; McKinney, Stanley, Plummer, Thompson, & Rorah, 2016).

Appreciation of fabric is essential to the process of creative zero-waste design. For instance, combining traditional crafts such as hand-weaving approaches with creative pattern design improved how designers perceive the fabric and create a new aesthetic (Niinimäki, 2013). Senanayake and Gunasekara Hettiarachchige (2020) explored this concept by introducing Dumbara weaving artisan to fashion design to tackle textile waste generated from the conventional Dumbara weaving approach. The authors used draping with rectangular pieces of fabric to be easier for the on-loom silhouettes weaving while considering the core value of the craft.

One of the main problems with zero-waste approaches is the uncertainty of the final design due to the continuous changes that happen during the

design development stage. Moreover, it can be challenging to translate a 2D zero-waste pattern into a 3D form. It might result in inconsistencies when implementing the final 2D pattern in 3D form, and either the fit, silhouette or aesthetic will not be as envisioned by the designer (James, Roberts, & Kuznia, 2016; McQuillan, 2019; Saeidi & Wimberley, 2018; Townsend & Mills, 2013).

Saeidi and Wimberley (2018) investigated applying another creative pattern making technique, 'transformational reconstruction' by Shingo Sato. The technique manipulates the design in 3D rather than 2D. This approach starts with a toile and a basic block laid on a dress form and creates the design lines, which then cut along those lines and turned into 2D pattern pieces. They designed three zero-waste garments to apply the jigsaw puzzle technique and the transformational reconstruction technique while considering fit and appearance. Transformational reconstruction appeared to be easier than using the jigsaw technique. It allows designers to think in 3D rather than 2D, eliminating the final design's unpredictability compared to traditional zero-waste methods, which can be beneficial to facilitate the integration of ZWFD in the industry.

4.2. Zero-waste fashion design: industrial implications and support tools

To understand the main factors affecting decision making in a business context when applying zero-waste design methods. McQuillan (2019) explored zero-waste pattern cutting with two different brands. She concluded that implementing the suggested zero-waste design is mainly affected by the value of textile waste and the extent to which the hierarchies in design and production are flexible. Additionally, the whole system is constrained by the financially imperative business model. Even with the increasing number of zero-waste design approaches, industrial adaptation to the zero-waste techniques in mass production remains one of the main problems of zero-waste design practices.

To examine the manufacturability of zero-waste fashion, Rahman and Gong (2016) explored the idea of 'transformable design' based on the zero-waste concept. It allows a garment to be transformed into multiple styles. However, it raised concerns regarding the manufacturability and marketability of the garments due to the complexity of the design process.

To remove the complexity of zero-waste design practices and facilitate the manufacturability of zero-waste garments, sustainable designers started developing zero-waste design support tools. McQuillan et al. (2018) explored multi-disciplinary research using 'User Modifiable Zero-Waste Fashion' (*Make/Use* tool). They applied a user-centred approach that allowed for garments to be made and modified with no fabric waste by providing ready-made patterns, prints and templates with modification options to help users change the design based on their preferences. Additionally, the tool has been used by international sustainable fashion brands and fast fashion such as Patagonia and H&M (Holly McQuillan et al., 2016; McQuillan et al., 2018). The *make/use* tool was explored by Scerbaka (2020) by making a zero-waste coat. The author posed that it will be challenging for inexperienced users to achieve good results using the system.

Another barrier to the industrial adaptation of zero-waste fashion is the problem of translating 2D patterns to 3D form, which always provides inconsistent outcomes (James et al., 2016; McQuillan, 2019; Saeidi & Wimberley, 2018; Townsend & Mills, 2013). This problem offers the opportunity for 3D modelling software such as 'CLO', which can visualise the behaviour of the used material in a true to life 3D garment simulation. McQuillan (2020a) suggested a transformation in the zero-waste design process using 3D software, eliminating multiple revisions of design and pattern between the conceptual idea and sample. McQuillan argued that utilising 3D software systems will facilitate integrating zero-waste methods into the industry (McQuillan, 2020a). The next section reviews the C&P methods for the marking planning problem and how it intersects with the ZWFD methods.

4.3. The intersection between zero-waste fashion practices and cutting and packing methods

A significant problem for manufacturers wanting to employ zero-waste pattern cutting is the lack of techniques applied in mass production. The research in ZWFD is only focused on designing one or two garments at a time without considering pattern grading in the process (Carrico & Kim, 2014; Niinimäki, 2013; Townsend & Mills, 2013). Ramkalaon and Sayem (2020) tackled this problem using AccuMark PDS to draft the patterns and create the marker layout using the embedded jigsaw and multiple clothing zero-waste approaches. Additionally, the authors utilising the 'inverse negative space' concept to make minor design components such as pockets, labels, gussets etc. The authors provided a framework for integrating zero-waste pattern cutting in mass production. They created a marker layout for sweatpants and hooded t-shirt in three sizes with fabric utilisation of over 98%. This utilisation rate is exceptional compared to traditional fashion production that typically does not exceed 85%

fabric utilisation (Carrico & Kim, 2014; Ramkalaon & Sayem, 2020).

Therefore, for ZWFD to be manufacturable, it is essential to have a simultaneous design process that combines pattern cutting, grading, and marker making to address the communication gap between designers and pattern makers (Ramkalaon & Sayem, 2020). Considering automating the marker planning process while using zero-waste approaches is worth researching. It will reduce the time required to design zero-waste garments instead of manual marker planning. Ramkalaon and Sayem (2020) mentioned the time-consuming aspect of their process, and they argued that basic styles such as sweatpants would not go out of trend. The marker layout can be implemented several times with minor tweaks to the colour and the prints. However, the problem of designing a non-basic zero-waste style remains. Therefore, the research gap in zero-waste fashion design and mass-production requires an innovative integration of other research paradigms such as the C&P research area.

As previously discussed, few C&P research papers focus on the nesting problems specifically tailored to the problem specifications in the apparel industry. Instead, C&P research focuses on the technical aspects of the problem involving finding efficient computational methods to deal with the complexity of the geometry of pattern pieces and how to search complex solution spaces. However, few papers have challenged some of the static assumptions around the fixed orientation of the shapes and the consistency of material quality.

Weng and Kuo (2011) developed a nesting system on the AutoCAD software, which uses C&P nesting optimisation techniques to convert pattern pieces drawn on AutoCAD into pixel matrices to facilitate the nesting. The main problem with this method is that the approach does not consider fabric properties while deciding the rotation angle, one of the main contributors to fabric waste during the cutting stage.

Tsao, Hung, and Vu (2021) proposed a rotation angle method to rotate the pattern width and flip the patterns (as mirrored images) with the rotated angles. They allocated the pieces from largest to smallest according to the length of the pattern piece itself; the optimisation algorithm they employed conserved 28% of the fabric length.

Enes and Kipöz (2020) investigated fabric waste from designs with different fabric properties such as nonwoven fabric, woven, symmetric, or asymmetric, and fabric width; they concluded that designing while considering fabric properties is essential to marker efficiency in mass production. When solving the nesting problem in the leather industry, it is necessary to consider the properties of the material, such as the leather hides and the irregularity of the surface, quality areas, defects, and holes, which make the problem very complicated from the geometrical point of view. Alves, Brás, Valério De Carvalho, and Pinto (2012) and Baldacci, Boschetti, Ganovelli, and Maniezzo (2014) developed optimisation algorithms that deal with the geometry of the leather pieces to find the best nesting solution.

In a case study from the textile industry, particularly the printing of soccer team logos Junior, Pinheiro, and Saraiva (2013) introduced a methodology that hybridises C&P methods that achieved 76.02% utilisation of fabric. M'Hallah and Bouziri (2016) integrated two main problems in apparel manufacturing; cut order planning (COP) and marker making (2D layout (TDL)). The COP is the problem that focuses on the cutting process of fabric for a given order such that the total cost of manufacturing is minimised. At the same time, TDL was employed to each COP to find the minimum length of the layout (M'Hallah & Bouziri, 2016). While these papers have taken a more focused approach to the textile industry, the design and the definition of the shapes remain static, which asserts the need for integrating both research areas to allow for a flexible zero-waste design process.

5. Conclusion and insights

This paper identifies similarities between the ZWFD and C&P research areas and possible collaboration in both fields. ZWFD emerged as a way to eliminate fabric waste from the cutting stage of fabric. Therefore, there are fundamental differences between the conventional and the ZWFD processes (Figure 5). The traditional fashion design process is mainly linear. The fashion designer is not involved in pattern cutting.

In contrast, in the ZWFD process, since pattern cutting is the primary step in the design, the fashion designer is involved in both design and make processes, making the process circular, leading to less waste (James et al., 2016). Two main issues with the current ZWFD: First, marker planning and grading can be difficult and time-consuming; for this reason, ZWFD is still not considered in mass production. Second, automated marker software are not designed to accommodate the zero-waste design process. Therefore, the ZWFD process needs to be integrated with the C&P process to adjust the design of automated markers (Figure 5).

The body of knowledge in the C&P area is extensive and resulted in the development of many powerful algorithms for solving the marker layout problem. Moreover, the computational tools provide useful information

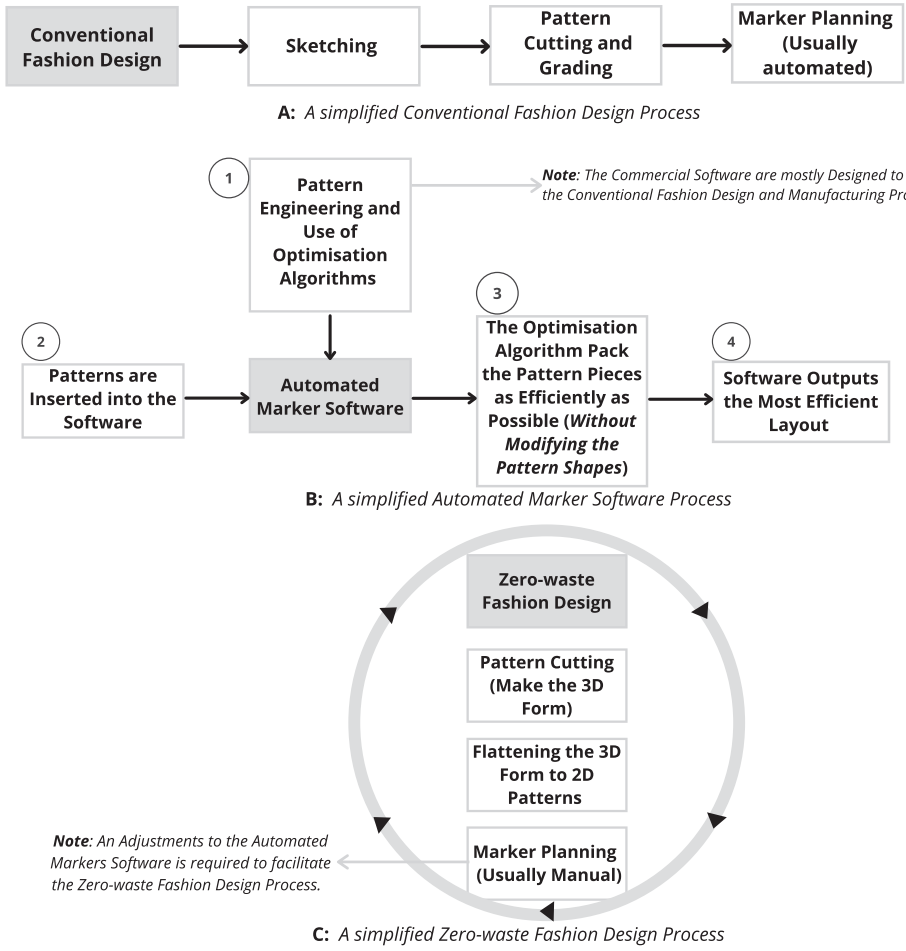


Figure 5. A Representation of Conventional and Zero-waste Fashion Design Processes with a Focus on Marker Planning.

about the opportunity to reduce waste in the layout. However, these methodologies assume that the pattern pieces are static and unchangeable. In contrast, in the ZWFD practices, the pattern pieces are not fixed and continuously changing to reach the objective of making aesthetically pleasing garments that are zero-waste. Hence, there is an opportunity to challenge the problem definition in the C&P paradigm and utilise the computerised geometric algorithms in providing information to help designers reach zero waste designs. For instance, pattern making methods such as jigsaw, embed jigsaw, tessellation, and creative cutting can be helpful in the algorithm design. The algorithm can be designed to provide multiple alternative tessellating pattern pieces similar to the design using computerised geometry tools.

To the best of our knowledge, this is the first review that links C&P and ZWFD research areas and proposes a different perspective to finding a solution to the pre-consumption textile waste. This paper contributes to the academic and ZWFD design practitioners' knowledge. It presents the key area of collaboration using a comparative literature search that identifies the design and system thinking when dealing with the waste minimisation problem.

Despite the contribution of this paper, there are some limitations. In this study, we only focused on ZWFD practices and techniques published from 2010–2021 in peer-reviewed journals since we concluded from our search that this period had the most published work related to our investigation. Also, extensive comparative research on zero-waste designs published in different ZWFD exhibitions, magazines, non-academic journals can provide valuable insights. The paper provides the fundamental support necessary for future interdisciplinary research between fashion designers and operational researchers to reach minimal to zero-waste solutions to the pre-consumption textile waste problem. Lastly, we suggest that practice-based research examining the relationship between the methodologies of ZWFD and C&P is needed to understand areas for improvements and collaborations better.

Disclosure statement

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References

Alves, C., Brás, P., Valério De Carvalho, J. M., & Pinto, T. (2012). A variable neighborhood search algorithm for the leather nesting problem. *Mathematical Problems in Engineering*, *183*, 28. doi:10.1155/2012/254346

Baldacci, R., Boschetti, M. A., Ganovelli, M., & Maniezzo, V. (2014). Algorithms for nesting with defects. *Discrete Applied Mathematics*, *163*, 17–33.

Bennell, J. A., & Oliveira, J. F. (2008). The geometry of nesting problems: A tutorial. *European Journal of Operational Research*, *184*(2), 397–415.

Bennell, J. A., & Oliveira, J. F. (2009). A tutorial in irregular shape packing problems. *Journal of the Operational Research Society*, *60*(1), S93–S105.

Carrico, M., & Kim, V. (2014). Expanding zero-waste design practices: A discussion paper. *International Journal of Fashion Design, Technology and Education*, *7*(1), 58–64. doi:10.1080/17543266.2013.837967

Carter, M. W., Price, C. C., & Rabadi, G. (2018). *Operations research: A practical introduction* (2nd ed.). Boca Raton: Chapman and Hall/CRC.

Choi, K. H. (2016). Practice-led origami-inspired fashion design: Out of the frame: Flight by paper plane. *International Journal of Fashion Design, Technology and Education*, *9*(3), 210–221. doi:10.1080/17543266.2016.1158872

Enes, E., & Kipöz, Ş. (2020). The role of fabric usage for minimisation of cut-and-sew waste within the apparel production line: Case of a summer dress. *Journal of Cleaner Production*, *248*, 119221. doi:10.1016/j.jclepro.2019.119221

Fletcher, K. (2008). *Sustainable fashion and textiles*. Design Journeys: Earthscan.

Holly McQuillan, J. A.-M., Menzies, G., Kane, K., Bailey, J., Fox-Derwin, E., O'Hara, J., & Stewart-MacDonald, B. (2016). Make/Use: A Modular System for Zero-Waste Fashion Retrieved 16 March, 2021, from https://makeuse.nz/

James, A. M., Roberts, B. M., & Kuznia, A. (2016). Transforming the sequential process of fashion production: Where zero-waste pattern cutting takes the lead in creative design. *International Journal of Fashion Design, Technology and Education*, *9*(2), 142–152. doi:10.1080/17543266.2016.1167253

Junior, B. A., Pinheiro, P. R., & Saraiva, R. D. (2013). *A hybrid methodology for nesting irregular shapes: Case study on a textile industry?*

McKinney, E., Stanley, A. E., Plummer, B., Thompson, K., & Rorah, W. (2016). Tacit magic: Understanding the principles behind nakamichi's creative pattern cutting. *International Journal of Fashion Design, Technology and Education*, *9*(2), 130–141. doi:10.1080/17543266.2016.1165740

McQuillan, H. (2009). Using design practice to negotiate the awkward space between sustainability and fashion consumption.

McQuillan, H. (2019). Hybrid zero waste design practices. Zero waste pattern cutting for composite garment weaving and its implications. *Design Journal*, *22*, 803–819. doi:10.1080/14606925.2019.1613098

McQuillan, H. (2020a). Digital 3D design as a tool for augmenting zero-waste fashion design practice. *International Journal of Fashion Design, Technology and Education*, *13*(1), 89–100. doi:10.1080/17543266.2020.1737248

McQuillan, H. (2020b). *Zero waste systems thinking: Multimorphic textile-forms* (Doctoral dissertation). Högskolan i Borås.

McQuillan, H., Archer-Martin, J., Menzies, G., Bailey, J., Kane, K., & Fox Derwin, E. (2018). Make/Use: A system for Open source, user-modifiable, zero waste fashion practice. *Fashion Practice*, *10*(1), 7–33. doi:10.1080/17569370.2017.1400320

McQuillan, H., & Rissanen, T. (2011). YIELD: Making fashion without making waste. *Twinset, The Dowse*.

McQuillan, H., Rissanen, T., & Roberts, J. (2013). The Cutting Circle: how making challenges design. *Research Journal of Textile and Apparel*, *17*(1), 39–49. doi:10.1108/RJTA-17-01-2013-B004

M'Hallah, R., & Bouziri, A. (2016). Heuristics for the combined cut order planning two-dimensional layout problem in the apparel industry. *International Transactions in Operational Research*, *23*(1-2), 321–353.

Nelson, R. (2013). *Practice as research in the arts: Principles, protocols, pedagogies, resistances*. Basingstoke: Palgrave Macmillan.

Niinimäki, K. (2013). A renaissance in material appreciation: Case study in zero waste fashion. *Journal of Textile Design Research and Practice*, *1*(1), 77–92.

Niinimäki, K., & Hassi, L. (2011). Emerging design strategies in sustainable production and consumption of textiles and clothing. *Journal of Cleaner Production*, *19*(16), 1876–1883.

Rahman, O., & Gong, M. (2016). Sustainable practices and transformable fashion design – Chinese professional and consumer perspectives. *International Journal of Fashion Design, Technology and Education*, *9*(3), 233–247. doi:10.1080/17543266.2016.1167256

Ramkalaon, S., & Sayem, A. S. M. (2020). Zero-Waste pattern cutting (ZWPC) to tackle over sixty billion square metres of fabric wastage during mass production of apparel. *The Journal of The Textile Institute*, *112*(5), 809–819.

Rissanen, T. (2005). From 15% to 0: Investigating the creation of fashion without the creation of fabric waste. *Creativity: Designer Meets Technology Europe*, *2005*, 27–29.

Rissanen, T., & McQuillan, H. (2016). *Zero waste fashion design* (Vol. 57). London: Bloomsbury Publishing.

Roberts, J. (2008). *Subtraction cutting school*: Center for Pattern Design.

Saeidi, E., & Wimberley, V. S. (2018). Precious cut: Exploring creative pattern cutting and draping for zero-waste design. *International Journal of Fashion Design, Technology and Education*, *11*(2), 243–253. doi:10.1080/17543266.2017.1389997

Scerbaka, A. (2020). Application of make/use platform for sustainable fashion design.*827*. doi:10.1088/1757-899x/827/1/012047

Senanayake, R., & Gunasekara Hettiarachchige, V. (2020). A zero-waste garment construction approach using an indigenous textile weaving craft. *International Journal of Fashion Design, Technology and Education*, *13*(1), 101–109. doi:10.1080/17543266.2020.1725148

Townsend, K., & Mills, F. (2013). Mastering zero: How the pursuit of less waste leads to more creative pattern cutting.

International Journal of Fashion Design, Technology and Education, *6*(2), 104–111. doi:10.1080/17543266.2013.793746

Tsao, Y.-C., Hung, C.-H., & Vu, T.-L. (2021). Hybrid Heuristics for marker planning in the apparel industry. *Arabian Journal for Science and Engineering*, *46*(10), 10077–10096. doi:10.1007/s13369-020-05210-1

Wäscher, G., Haußner, H., & Schumann, H. (2007). An improved typology of cutting and packing problems. *European Journal of Operational Research*, *183*(3), 1109–1130.

Weng, W.-C., & Kuo, H.-C. (2011). Irregular stock cutting system based on AutoCAD. *Advances in Engineering Software*, *42*(9), 634–643.

WRAP. (2019). A case study on management of leftovers from garment manufacturing in Sri Lanka (Vol. 2021).