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What is the Next Step for Zero-Waste Fashion?

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Abstract Over the past decade, Zero-waste pattern making has been attracting attention as a breakthrough sustainable fashion design development method to reduce waste generated during production process. Although many designers have been developing creative zero-waste design methods, more systematic and standardized systems are needed to be commercialized in actual fashion industry. This study proposes to use a modular system as a solution to overcome the limitations of existing zero-waste pattern making methods. Therefore, the purpose of this study is to present a new methodology for sustainable fashion through the development of a zero-waste fashion design and construction system using the concept of a module system based on three-dimensional digital clothing technology. Through researching previous studies related to modular system fashion, the sustainable characteristics of the modular system were derived as, Personalized transformability, Simplicity, and functional extendibility. Based on these research results, a total of five looks for women's clothing modular zero-waste fashion design using the three-dimensional digital fashion design method were presented as virtual prototypes. Through this study, it is expected that modular system fashion design using 3D digital clothing technology will meet various needs of consumers while presenting a new methodology for productivity and popularization of sustainable fashion.

Keywords Zero-Waste Fashion, Modular System, Digital Fashion, Sustainable Fashion

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Introduction

The Industrial Revolution and overseas production methods enabled mass production, which brought fast fashion trends to the fashion industry. Fast fashion oversupplied large quantities of products to consumers at low prices, and vast amounts of inventory that were not chosen by consumers turned into clothing waste (Jin & Shin, 2021). In addition, due to the mass production system of fast fashion, the vast amount of textile waste generated in the production process also has a huge adverse effect on the environment. According to UN data, greenhouse gases emitted by the fashion industry are between 28% of the world's total emissions, more than those of the aviation and transportation industries combined. In addition, the textile industry has been blamed for the plastic flowing into the sea over the past few years (United Nations Economic Commission for Europe, 2018).

Over the past decade, the fashion industry has made various attempts to avoid existing industrial systems that harm the environment and build sustainable fashion systems. Among them, a design and construction method aimed at minimizing textile waste generated in the production process is called zero-waste fashion. Zero-waste pattern making, a construction technique that minimizes waste generated in the production process, has been developed by many designers.

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Zero-waste pattern making, which simultaneously plans pattern layout on fabric (marker making) from the initial design stage, is currently being developed and studied, but it is true that a more systematic and standardized system is needed to be used in the actual industry (ElShishtawy et al., 2022). Meanwhile, due to the rapid development and popularization of the digital industry, the exchange of knowledge and information in modern society is simultaneous and diversified. As a result, consumer opinions and requirements have become the most important factors in designing and producing products. In line with this consumer-centered design trend, modular system designs that consumers can assemble and disassemble themselves are being developed and produced more actively than ever across the design industry. In the fashion industry, fashion design students or small brands have often developed designs using modular systems, but the public response was significantly lower than in other design industries. However, WGSN, a trend prediction company, cited modular fashion as one of the five key trends in the future in a report titled 'Five Key trends for 2021 and beyond: Fashion'. This means that modular system fashion is moving from a conceptual area as a way of expressing fashion to an area deemed commercially valuable (Vaid, 2021). In addition, the modular pattern cutting method using the simplicity of the module form is one of the representative methods of zero-waist pattern making. As such, the use of the module concept has great potential as a solution to overcome the inefficiency of existing zero-waste pattern making and achieve sustainable fashion while meeting the subdivided needs of consumers. Besides, the use of 3D digital closing technology, which is emerging as a key technology in the future fashion industry, can minimize the production of samples that are produced and discarded in the design process. In the case of zero-waste pattern making, which requires pattern layout design from the design process, it is highly valuable to use 3D digital clothing technology that can check the results of pattern shapes and layout modifications in real time (McQuillan, 2020). Therefore, the purpose of this study is to present a new methodology for sustainable fashion through the development of a zero-waste fashion design and construction system using the concept of a module system based on three-dimensional digital closing technology. The contents and methods of this study are as follows. First, the concept and characteristics of modular system fashion and zero-waste pattern making are analyzed through reviewing previous studies. second, based on the analysis of previous studies, the characteristics of modular system fashion were derived from the perspective of sustainable fashion, and the design and pattern making method of this study was embodied based on this. Third, based on the derived results, a total of five modular zero-waste women's clothing designs is produced using three-dimensional digital closing technology.

Literature Review

Concept and Methods of Zero Waste Pattern Making

There are two types of textile waste that we need to reduce to achieve sustainable fashion. One is clothing waste that is discarded after clothing is purchased and worn by consumers, and the other is fabric waste generated during the production process of clothing. About 15% of the amount of fabric for making clothing is discarded as waste during production cutting (Kook, 2014). And according to statistics from the Ministry of Environment of South Korea, textile waste discharged during production increased from 1.12 million tons in 2010 to 4.51 million tons in 2018 (Lee, 2021). These wastes not only represent the loss of economic costs, time and labor required to produce textiles and textiles, but also, most unfortunately, have serious adverse effects on the environment (Rissanen, 2013). Therefore, zero-waste fashion design, which refers to fashion designs and construction methods in which there is no waste generated during the production process or minimum waste is discharged, are being actively researched and developed. In detail, it can be divided into the use of materials that decompose 100% on the ground even if discarded after use, Zero-waste pattern making that creates patterns to minimize fabric waste generated in the cutting process in production, and modularization to maximize product usage time (Yoon & Yim, 2015). As a result, it has attracted attention as a groundbreaking way to realize sustainable fashion, and many designers have developed and suggested creative pattern making methods.

Limitation for Commercialization

A growing number of designers are studying zero-waste patternmaking in various ways to achieve the goal of sustainable fashion, but for now, it is still a research topic with high potential (Kim & Kim, 2018). In fact, clothes designed and produced using zero-waste pattern making in the fashion industry are extremely rare, and there are still many tasks to be solved to be commercialized (Li et al., 2018). Representative examples include the possibility of size grading to maintain a zero-waste pattern composition even if it is graded in various sizes, and unnecessary fabric surplus treatment in finished products designed to reduce cutting waste (Carrico & Kim, 2014). Besides the grading issue, Marker (pattern layout) software automated based on existing systems cannot accommodate the zero-waste pattern design process. Therefore, the commercialization of zero-waste pattern making requires the development of marker software for zero-waist pattern making by building algorithm systems through numerous data collections (ElShishtawy et al., 2022). In addition, in the case of the jigsaw puzzle cutting method, designers and pattern makers cannot work separately due to the nature of the work that requires the pattern pieces to be accurately inserted like puzzles, and they must spend a lot of time designing and developing patterns. In the case of a tessellation or small modular cutting method, the disadvantage is that it is difficult to predict 100% of the fit or shape of the finished work when selecting the shape of the module for the first time (Saeidi & Wimberley, 2018). In 2022, Carrico and her team developed a method of inserting bands that crosses the grading point of clothing diagonally to compensate for the limitations of grading zero-waste pattern. This method achieves size grading by adjusting the width of the band while maintaining the size and shape of the original zero-waste pattern. However, this method lacked aesthetic unity as the band inserted into each size were different due to grading. In addition, there was a disadvantage that additional discussions with the sewing team were required because there were many difficulties in sewing where the grading bands gathered (Carrico et al, 2022). Therefore, to commercialize zero-waste pattern making, various studies from new perspectives must be continuously conducted.

Concept of Modular System

The dictionary meaning of a module is a standard or unit of measurement, a series of standardized arbitrary units for use together. (Merriam-Webster) That is, a module serves as a standard measurement unit arbitrarily determined to complete many buildings or products in the same proportion or form. The establishment of such module standardization has become an important factor in the industry for the modernization of the complex production process of building materials, parts, and assemblies. Therefore, products utilizing the efficiency of module systems are actively being developed in various industries, starting with the architecture industry (Lee, 2017). Ironically, however, in modern society, it is used as a means of accommodating various tastes of consumers (Yoon & Lee, 2014b). This is because standardization and flexibility of modular systems are customizable, and individualization is possible even if it is a mass-produced product (Hur & Thomas, 2011). In other words, the modular system allows each part to be dismantled and reconfigured with other parts, which is highly utilized and allows various productions in design, so it can develop products suitable for satisfying the needs of modern consumers who want to express their tastes in a unique way. Modular systems are based on architectural, engineering, and scientific concepts that seek maximum diversity with minimal materials, while modularity can be explained in the design context. Modularity refers to the degree of autonomy to reconstruct, add, or remove components of a product and the structural configuration that enables or prohibits them. (Baldwin & Clark, 2000). Structural autonomy is one of the key elements of zero-waste pattern making which developed based on creative pattern composition. Based on the flexible configuration of the module unit, modularity, which enables creative pattern arrangement and shape development, has been utilized in zero-waste fashion design by designers such as Galya Rosenfeld and Davide Andersen (Kook, 2014). The flexible nature of modular system offers a variety of possibilities in fashion design that consumers can transform and wear what they want instead of telling consumers how to wear clothes (Li et al., 2018). In a modern society facing an era of hyper-personalization, zero waste design development, which combines the architectural concept of a modular system with a design that enables autonomous modularity, is future-oriented and has high research value.

Characteristics of Modular System Fashion

Sustainable fashion has been developed by small conscious brands in the past. However, global fashion giants and luxury brands, which have led fast fashion, are taking the lead in developing sustainable fashion products through various attempts and research. This means that the sustainability of fashion design has become an essential factor, not an optional factor for the future fashion industry (Kook, 2014). The characteristic of the modular system that allows consumers to freely assemble and disassemble clothes and use them for various purposes through modularization of single clothes is a future-oriented sustainable fashion system. In the study of Lim and Lee (2012), the modularity of clothing was classified into composition, design, and formation, and based on this, the usefulness of clothing modular design was derived as economical, simplicity, promptness, flexibility, functional, and creativity.

In the research of Yoon and Lee (2014a), the characteristics of modular systems in architecture and product design cases were classified into individuality, simplicity, combination, repeatability, extensibility, variability, diversity, and autonomy, and based on this, the formative characteristics of the modular system in fashion were classified and analyzed as simplicity, diversity, variability, and extensibility. According to Li et al. (2018), in this “fast fashion” market, modular system design that can meet both eco-friendly needs and creative freedom of expression is likely to be a groundbreaking alternative for the future fashion industry. And they analyzed the environmental value of modular design as diversity and flexibility and continuity. In Lee, H. C.’s study, the characteristics of the modular system were subdivided and analyzed based on form, function, and sensitivity, and as a result, it was derived as standardization, combinability, decomposition, multi-function, and independence. In addition, each characteristic is not in an exclusive relationship with each other and appears simultaneously and complexly within the design (Lee, 2020). According to Lee (2023), the systemic characteristics of modular design used in fashion can be classified into assembly type, mobile type, and interchangeable type, and the sustainable characteristics of modular system design were analyzed as simplicity premised on multifunctional combinations, variability premised on creative reunion, and organicity premised on restorative connections. In previous studies, the characteristics of overall modular system fashion were studied and analyzed. However, as studies on sustainability in various fields are more active than ever, it is necessary to re-analyze the contents derived from previous studies from the perspective of sustainable fashion.

Table 1. Characteristics of modular system fashion in previous research

Researcher	Characteristics of modular system fashion
Lim & Lee (2012)	Economical, Simplicity, Promptness, Flexibility, Functional, Creativity
Yoon & Lee (2014a)	Simplicity, Diversity, Variability, Extensibility
Li et al. (2018)	Diversity, Flexibility, Continuity
Lee (2020)	Standardization, Combinability, Decomposition, Multi-function, Independence
Lee (2023)	Simplicity, Variability, Organicity

Sustainability of Modular System

In the study of Jin and Shin, the three goals to be achieved using advanced technology in the 4th industrial era to solve the problems of the existing fashion industry were hyper-personalization, environmental sustainability, and finally productivity (Jin & Shin, 2021). This is in line with the goal of this study to pursue the popularization of sustainable fashion through zero-waste modular patternmaking research and modular system design development. Therefore, this study analyzed the characteristics of modular system fashion required by the sustainable fashion industry by dividing it into 1) personalized transformability, 2) simplicity, and 3) functional extendibility.

Personalized Transformability

In modern society, expressing individual tastes and

Figure 1. Meccano (Emmanel A. Ryngaert, 2016) (Antwerp Fashion Department, n.d.)

Figure 2. Modular Dress 2.0 (Wei Hung Chen, n.d.) (The New School, Parsons, n.d.)

individuality is becoming more common, and design lacking diversity is difficult to expect consumer response (Yoon & Lee, 2014a). This consumer-centered design trend is used in various industries in conjunction with the assembly and decomposition characteristics of modular systems. The BESPOKE trend of home appliances is the most common example, and in the fashion industry, more and more brands are building consumer-participating interactive online platforms by incorporating modular systems into customized collections (Li et al., 2018). Meccano collection by Emmanuel A. Ryngaert (Figure 1) and Modular dress 2.0 by Wei Hung Chen (Figure 2) can be said to be an example of the consumer-centeredness of the modular system. Both designs can be assembled and disassembled directly by consumers and transformed into the desired shape or purpose. These consumer-centered designs allow consumers to freely express their tastes and senses and increase the utility value of clothing, which can be expected to increase the life of clothing.

Simplicity

The simplicity of the module form can be said to be the basic characteristics of the original module development to enable mass production through standardization. Even in the architectural design in which the modular system was first introduced, the simpler the module form or combination method, the more colorful and new design development is possible (Yang, 2008). These characteristics also apply to clothing composition, and the simple module form is directly related to the productivity of clothing and is one of the important characteristics that allows consumers to easily understand and use the clothing composition. Paco Rabanne's 1960s inspired 2023 F/W Collection dress (Figure 3) and Sebastian Errazuriz's multiples zipper dress (Figure 4) are examples of the simplicity of modular design.

Functional Extendibility

The biggest feature and advantage of the module is that it can be used in various way through shape deformation and compatibility (Kim, 2009). The sustainable transformable fashion design work created by Osmud Rahman and Minji Gong (Figure 5) and Buildable clothing by Marfa Stance (Figure 6) are examples of the extendibility of modular systems. In addition, the denim series introduced by Christopher Shannon in the 2017 S/S collection (Figure 7) shows diversity through the compatibility of the composition parts.

This is the same system that if we lose the components of Lego toys, we can only buy the missing components again, not buy the entire product. Functional extendibility can be said to be the simplest and the most economical method among various methods to reduce clothing waste. The flexible compatibility of modular system fashion is not only economical, but also an important characteristic that can achieve sustainable fashion popularization through mass customization.

Figure 3. Paco Rabanne, Fall 2023 (Wei, 2023)

Figure 4. Multiples Zipper dress (Errazuriz, 2003).

Figure 5. transformable fashion design using 39 garment pieces by Rahman, O., & Gong, M.(Rahman & Gong, 2016, pp.240-241)

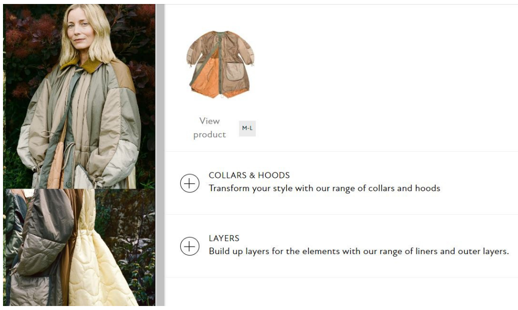


Figure 6. Buildable parachute Jumper (Stance, 2019)

Figure 7. Christopher Shannon, 2017 S/S (Vogue, n.d.)

Design Development

Using the characteristics of modular system fashion analyzed from the perspective of sustainable fashion derived from previous research and complementing the limitations of zero-waste patternmaking, we designed a zero-waste modular fashion collection based on three-dimensional digital closing technology. By actively reflecting the concept and characteristics of the module in pattern making, we intend to propose a sustainable fashion system with productivity and utility.

The design theme is “Give a name to the piece No. 1”, meaning that a single pattern that usually means only the component of clothing has an independent unique meaning through modular system design. In the case of module textile design, by using the Op art pattern, the formative limitations due to the simplicity of the independent module were supplemented and the compatibility of the same module shape was expressed. Op art, which creates an illusion through a combination of geometric lines and spaces accurately implemented based on mathematical calculations, can be interpreted indefinitely depending on the viewer’s gaze (Lee, 2014). The characteristic of Op art is in line with modular system designs that express diversity and flexibility through repetition and deformation of simple form. Besides, each module unit is designed to be assembled and disassembled independently using a zipper or snap in order to achieve transformability and functional extendibility.

Zero Waste Modular Patternmaking

The most common method of making modular zero-waste patterns is the method of manufacturing and assembling many small-sized, fixed-shaped modules. While this method has the advantage of being able to manufacture costumes to fit the curves of the human body and transform them into various types of designs, it can be difficult for users to assemble and disassemble clothes by utilizing the characteristics of the modular system. Therefore, in this study, the size of each independent module was made into a size that anyone can easily recognize as a pattern for each part of the human body (front bodice, back bodice, sleeve, etc.). On the other hand, the grading problem,

Even if the pattern is graded by shaping it into a square shape, the shape is maintained, and the fabric disposal rate is not increased. In addition, by limiting the type of independent modules, compatibility and productivity of the modular system were maximized. A total of 13 independent modules manufactured in this way were designed to be compatible with each other, completing a five-design women’s clothing. Each independent module was named Module A to J, and each form is shown in Figure 8.

For module A, the module that creates the most basic form of the upper front bodice pattern, which includes the neckline curves and shoulder slope that are inevitably required to implement the human body curve. Module B was constructed as a module that created the basic shape of the most part of the upper back bodice and included curves around the neck and diagonal shoulder lines, just like module A. Module C is used for main bodice and upper pants. The

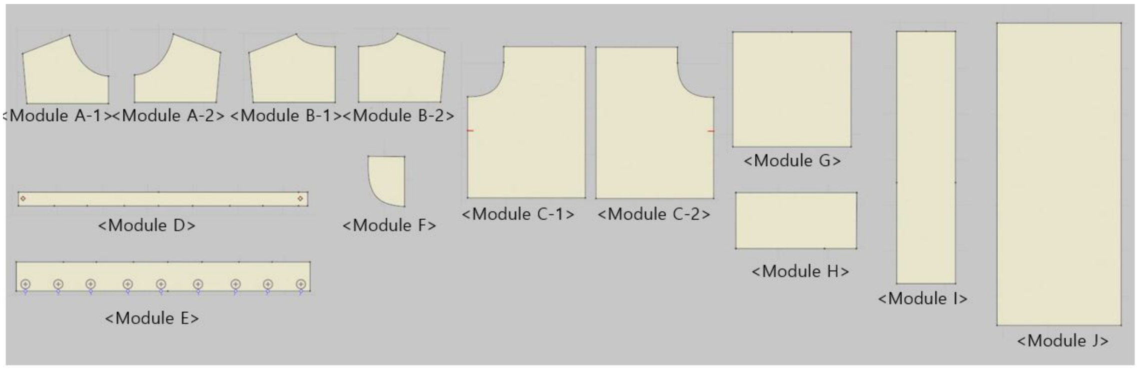


Figure 8. Shapes of Modules

cut piece to create a curve of the armhole or trouser clutch is used as a pocket pattern and sleeve pattern in the collection as module F to prevent fabric waste. Module D was used as a belt. Module E was used as the bottom base pattern of the skirt. Module G has the same length of horizontal side as module C and is close to square and is used as a module of a skirt or top. Module H is a module with the same horizontal length as modules C and G and was used as the top part of the skirt or bottom part of the top. Module I used for the side of the pants. Module J played a role in giving a three-dimensional effect to the shoulders and skirts, adding the lively and design elements of the collection.

Zero Waste Modular System Design Result

Based on these research results, a total of 5 looks for women's clothing modular zero-waste fashion design using the three-dimensional digital fashion design method were presented as virtual prototypes. The connection between modules in the entire collection is configured to use a zipper, enabling attachment and compatibility. However, when the length of the connection module surface is different, it is designed to be detached with a snap. Specific explanations for each look are shown in Table 2.

To explain in detail, look 1 consists of top and pants, and modules A, B, C, D, F, H, and I were used. Module A was used as the top pattern of the front, and module B was used as the top pattern of the back. Module C was used as a front and back bodice pattern, and as a middle and bottom of trousers. Module D was used as a belt, and module F was used as a pocket for the top. Module H, it was used as the top part of the pants connected to the belt. And Module I, it was used as a side plate for pants.

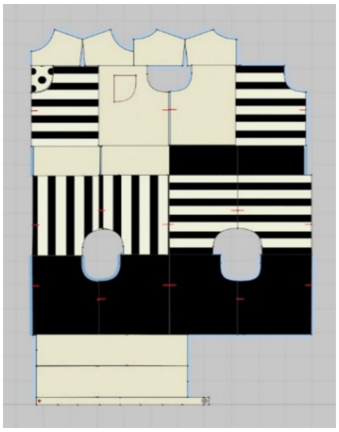
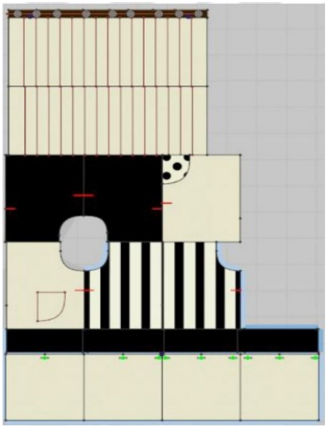
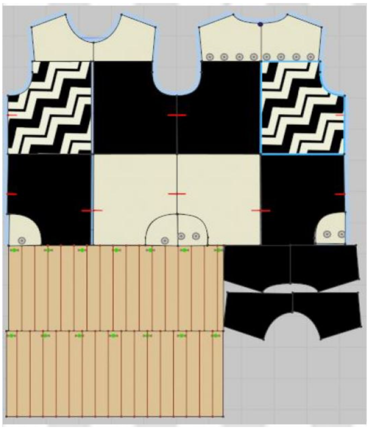
Look 2 is composed of a Top and a skirt, and modules C, D, F, G, H, and J are used. Module C was used as front and back bodice pattern and the lower left of the skirt. Module D was used as a belt, and module F was used as a pocket decoration on the bodice. Module G was used as the front and back top of the skirt connected to the belt, and module H was used as the bottom of the top. Module J was used as a pattern on the lower right side of the skirt. To add 3D design elements, a thick top stitch was sewn on module J to enrich the texture of the fabric. After cutting the fabric, the remaining fabric will be patchwork to make the hood.

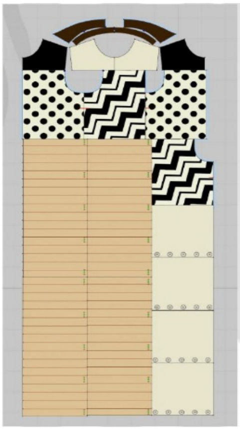
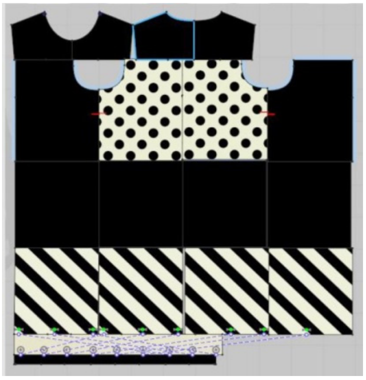
Look 3 is a one-piece dress and consists of modules A, B, C, F, and J. Module A was used as the upper front pattern and skirt hem, and module B was used as the upper back pattern and skirt hem. Module C was used as the front and back bodice pattern and the top part of the one-piece skirt. Module F was used as a top part of sleeve pattern, and module J was used as sleeve and draping pattern for the back.

Look 4 is also a one-piece dress, consisting of modules A, C, G, and J. Module A was used as a sleeve drape pattern, and module C was used as a front and back top pattern. Module G was used as a pattern in the middle of the dress, and module J was used as draping pattern at the bottom of the dress.

Look 5 consists of modules A, B, C, D, E, and G with a top and skirt design. Module A was used as a pattern for the

Table 2. Development of zero waste modular system design

Look 1	Pattern Layout	Module Composition
		Module A: Front Top Module B: Back Top Module C: Bodice, Pants Module D: Belt Module F: Pocket Module H: Pants Top Module I: Pants Side
Look2	**Pattern Layout**	**Module Composition**
		Module C: F/B Bodice, Skirt Module D: Belt Module F: Pocket Module G: F/B Skirt top Module H: F/B Top bottom Module J: F/B Right Skirt
Look3	**Pattern Layout**	**Module Composition**
		Module A: Front Top, bottom Module B: Back top, bottom Module C: F/B Bodice, Skirt Module F: Sleeve top Module J: SlV/BK Drape

Look4	Pattern Layout	Module Composition
		Module A: Sleeve Module C: F/B Top Module G: Bodice Module J: Skirt Drape
Look5	**Pattern Layout**	**Module Composition**
		Module A: Front Top Module B: Back Top Module C: F/B Bodice Module D: Belt Module E: Skirt bottom base Module G: F/B Skirt

upper front pattern, and module B was used as upper back pattern. Module C was used as front and back bodice pattern, and module D was used as a belt. Module E was used as skirt bottom base pattern. Module G was used as front and back skirt.

This design development process started with designing in various configurations using a limited number of modules. Although it is difficult to see directly from the results of the 3D work, each module is designed to be assembled and disassembled independently using a zipper or snap. In addition, modules of the same shape can be customized with various opt-arts. By assembling and disassembling modules of various pattern designs, consumers can customize and wear the clothes of the desired shape and design. The independence of module units is an important key point not only to achieve personalized transformability, but also to have functional extendibility by transforming freely depending on the situation. On the other hands, it was not possible to create a pattern that fits the curve of the human body by using simple squared shape of module unit, but it achieved a pattern layout that minimizes cutting waste and further suggested alternatives that overcome the limitation of zero-waste pattern making in grading. In addition, the simple module shape is an important factor for consumers to customize themselves, help with structural understanding, and increase consumer convenience when assembling/deconstructing or transforming clothes.

Conclusion

It is the biggest challenge of the modern fashion industry to realize environmentally sustainable fashion while pursuing the satisfaction of modern consumers with various personalities and tastes. Many designers are conducting research to popularize sustainable fashion in various ways. Among them, various methods of zero-waste patternmaking have been continuously developed and studied to reduce fabric waste generated in the production process. However, it is true that there was a limit to productivity due to grading and systematic problems. The results of planning and developing a modular system zero-waste fashion design using 3D digital closing technology to supplement these limitations and enhance the utility and practicality of single clothing are as follows.

First, Standardization of independent module units has increased the transformability and multifunctionality of modular system clothing to maximize the utility value of clothing. As a result, it has the effect of extending the lifespan of clothing. In addition, the simple form of independent modules has the potential to be graded in various sizes, which can result in increased productivity and popularization of zero-waste pattern making.

Second, it was possible to minimize the time and economic cost of manufacturing basic module units, assembling/disassembling modules, and testing module compatibility between appearances with 3D digital clothing technology. In addition, since fabric waste is not generated in the sample production process that repeats various attempts, it is an efficient method to realize sustainable fashion even in the design stage before the production stage.

Third, by using the characteristics of the Op art, which shows dynamic effects through repetition of static and simple patterns, as a pattern design of independent modules, it was possible to add vitality and diversity to the simple form of modules and increase visibility between independent modules.

Through the results of this study, it is expected that modular system fashion design using 3D digital clothing technology will meet various needs of consumers while presenting a new methodology for productivity and popularization of sustainable fashion, which is an essential research task of modern fashion.

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