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Topology optimisation considering subjective preferences: current progress and challenges

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Abstract

Topology optimisation techniques can redistribute given materials to their most-needed locations to generate efficient and innovative structural designs. However, these techniques are typically performed based purely on structural performance. Hence, the solutions could be of low value in specific practical applications, as they may not always satisfy all design requirements, including factors like aesthetic quality. Recently, a few studies have reported that introducing subjective preferences into topology optimisation techniques can result in more satisfying structural designs so that users do not need to passively accept the conventional optimisation results. This paper provides a brief overview of the state-of-the-art in topology optimisation techniques that consider subjective preferences. The techniques are classified into three groups based on when subjective interventions are introduced: pre-processing, post-processing and interactive processing strategies. The advantages and limitations of each group are discussed, as are the technical challenges involved in extending these new techniques. Overall, this paper aims to serve as a helpful guide for future developments of topology optimisation techniques that consider subjective preferences, hoping to create more practical and customised structural designs that better meet the needs of users.

Keywords: topology optimisation, subjective preferences, structural design, interactive design

1. Introduction

Topology optimisation is an effective strategy to generate lightweight, efficient and innovative structural designs by redistributing underutilised materials to their most-needed locations in continuous design domains [1]. Conventional topology optimisation techniques are typically performed based on finite element analysis (FEA) with the elements used to represent the given materials. A widely used topology optimisation technique is the bi-directional evolutionary structural optimisation (BESO) method; it allows inefficient and efficient elements to be simultaneously removed and added, generating clear 0/1 designs to represent material density distributions [2]. As shown in Figures 1(a)–(e), the BESO method has been employed in numerous novel practical applications, including bridges [3], furniture [4] and architectural designs [5,6].

According to [7], topology optimisation that focuses only on improving structural performance may not achieve solutions that meet all design requirements, such as aesthetics. Therefore, recent studies have extended the BESO method (i.e., multi-solution strategies) to produce diverse and competitive solutions, offering users a variety of design choices [7]. Specifically, such strategies trade off a minor decrease in the structural performance (e.g., 3% stiffness) of the 'best design' in exchange for multiple topologically different and structurally efficient solutions. Multi-solution strategies include parameter-based [8,9], sub-domain-based [5,10,11], constraint-based [12,13] and weight-based strategies [10,11,14].

It should be noted that design options generated from multi-solution strategies may include many undesired candidates due to differences in personal preferences [15]. Hence, designers must spend significant time and effort to evaluate each option to select a satisfactory one, leading to a costly design exploration process [15]. As reported in [16], a piece of design work can reflect the designer's personality, taste and thoughts, emphasising the need to introduce subjective preferences into the design process rather than selecting from multiple options. To this end, recent studies have developed various computational design methods incorporating subjective preferences [16–19]. However, only a few studies have implemented the concept of 'subjective preferences' into topology optimisation [5,14,16]. In this context, a comprehensive review of the current topology optimisation methods considering subjective preferences is necessary to better understand the progress, potential and challenges.

The objective of this paper is to offer a clear understanding of topology optimisation methods that incorporate subjective preferences. To achieve this goal, we conduct a critical review of state-of-the-art research in this field. By examining the progress made so far, the potential and challenges of these methods can be better understood. This will help to improve the development of future topology optimisation techniques that can produce structural designs that better reflect subjective preferences and ultimately lead to more efficient and effective design processes. Section 2 provides a detailed review of these methods, while Section 3 discusses the existing challenges and future possibilities. Finally, Section 4 presents a conclusion.

Figure 1. Applications of the BESO method in structural design: (a) bridge [3]; (b) chair [4]; (c) high-rise building [5]; (d) roof [6]; (e) table [4].

2. Topology optimisation techniques considering subjective preferences

2.1. Selection criteria

Shortlisted research papers discussed in this paper are selected based on the following criteria:

- The underlying computational design method must be topology optimisation, such as the BESO, SIMP and level-set methods.
- The topology optimisation method must allow users to input their subjective preferences, such as aesthetics, design concepts and artificial intervention, among others.
- The incorporation of subjective preferences must have an impact on the generation of optimal structural topologies.

Note that the term 'subjective preferences' may be expressed in different ways in different studies. A few phrases were useful in finding the shortlisted research papers: 'topology optimisation based on artificial intervention', 'preference-based topology optimisation' and 'topology optimisation considering aesthetics'.

Based on the above criteria, we have found three most-related research papers about 'topology optimisation considering subjective preferences', including [5], [14] and [16]. The three interrelated studies put forward a total of five topology optimisation methods that incorporate subjective preferences. These methods can be classified into three groups based on the conditions of subjective interventions in topology optimisation, as shown in Figure 2. They include 'pre-processing', 'post-processing' and 'interactive processing' strategies, corresponding to subjective interventions 'before', 'after' and 'during' topology optimisation, respectively. Details of each group are summarised in Sections 2.2−2.4.

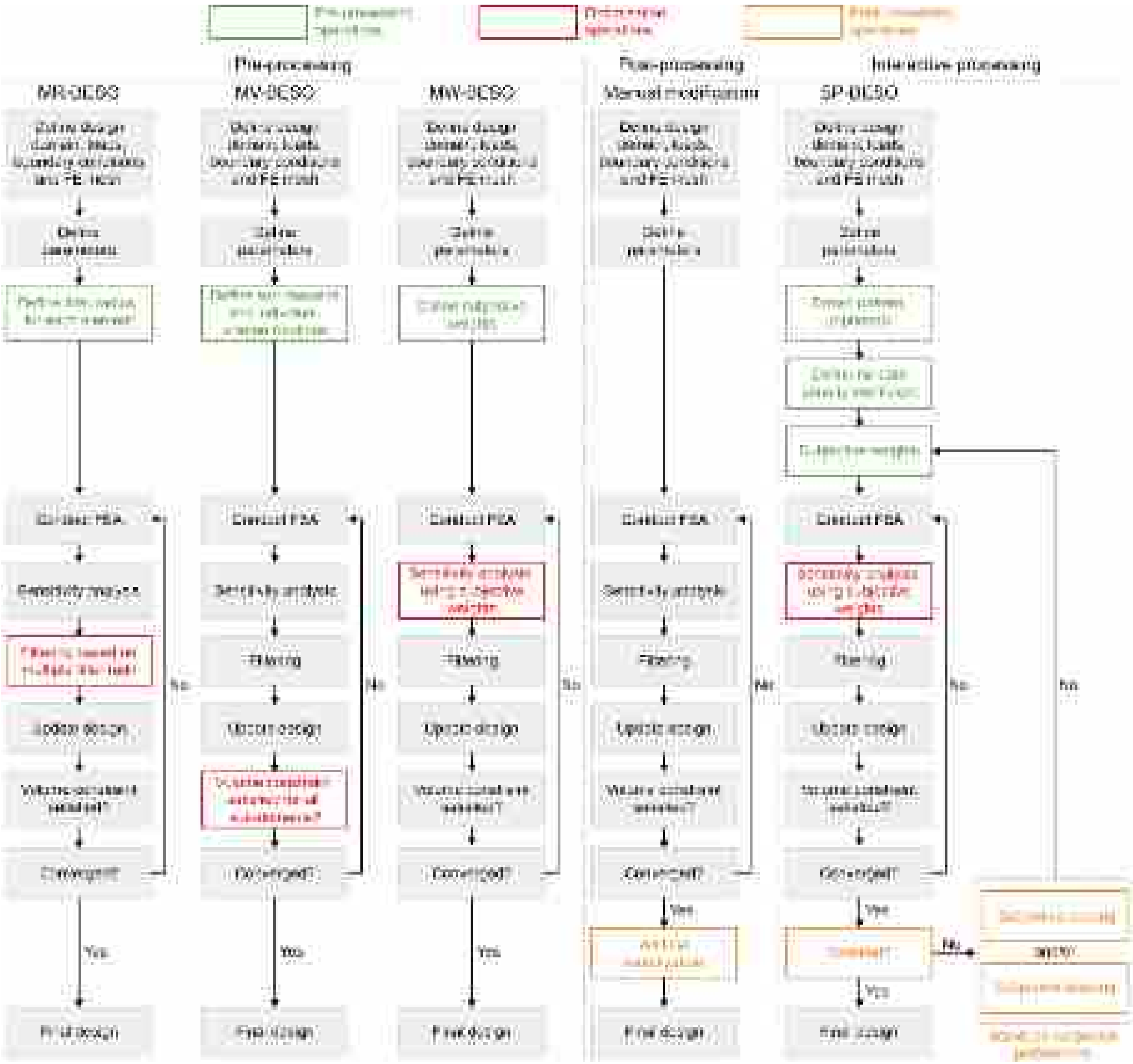

Figure 2. Computational workflow of topology optimisation methods considering subjective preferences. These five methods can be categorised into three groups: pre-processing, post-processing and interactive processing strategies.

2.2. Pre-processing strategy

In the pre-processing strategy, users are required to subjectively define local settings, such as weights of elements and optimisation parameters, before carrying out topology optimisation. Yan et al. [5] proposed three extensions of the BESO method based on the pre-processing strategy to consider subjective preferences, including multi-radius BESO (MR-BESO), multi-volume BESO (MV-BESO) and multi-weight BESO (MW-BESO). Figure 3 provides a clear graphical comparison of these three methods with the original BESO method. Note that in the original BESO method (see Figure 3(a)), there is only a uniform filter radius, a global volume constraint and equal weights for all elements (i.e., one weight). However, in [5], the number of these optimisation parameters is increased to expand design freedom to include subjective preferences.

- MR-BESO (see Figure 3(b)) empowers designers to specify multiple filters of different sizes in different areas of the design domain. This feature enables designers to regulate the minimum sizes of structural members based on their subjective preferences and ensure that the design requirements of member sizes at specific regions are met.
- MV-BESO (see Figure 3(c)) first divides the design domain into multiple sub-domains, where the elements in each sub-domain are independently added or removed during topology optimisation in the same evolutionary iteration [10]. Using MV-BESO, designers can pre-define different local volume fractions for each sub-domain based on their subjective preferences or design requirements, resulting in customised structural designs.
- MW-BESO (see Figure 3(d)) allows designers to adjust the importance of elements by introducing elemental weights based on subjective preferences. By assigning higher weights to specific elements, users can influence the outcome of the optimisation process and potentially achieve a design that better meets their needs. These weighted elements are given a higher rank during sensitivity analysis, which increases their likelihood of being retained in the final topology. Notably, the importance level of subjective preferences in MW-BESO is controlled by two weighting coefficients, enabling the final structural topology to be subjective- or performance-driven, depending on the design requirements.

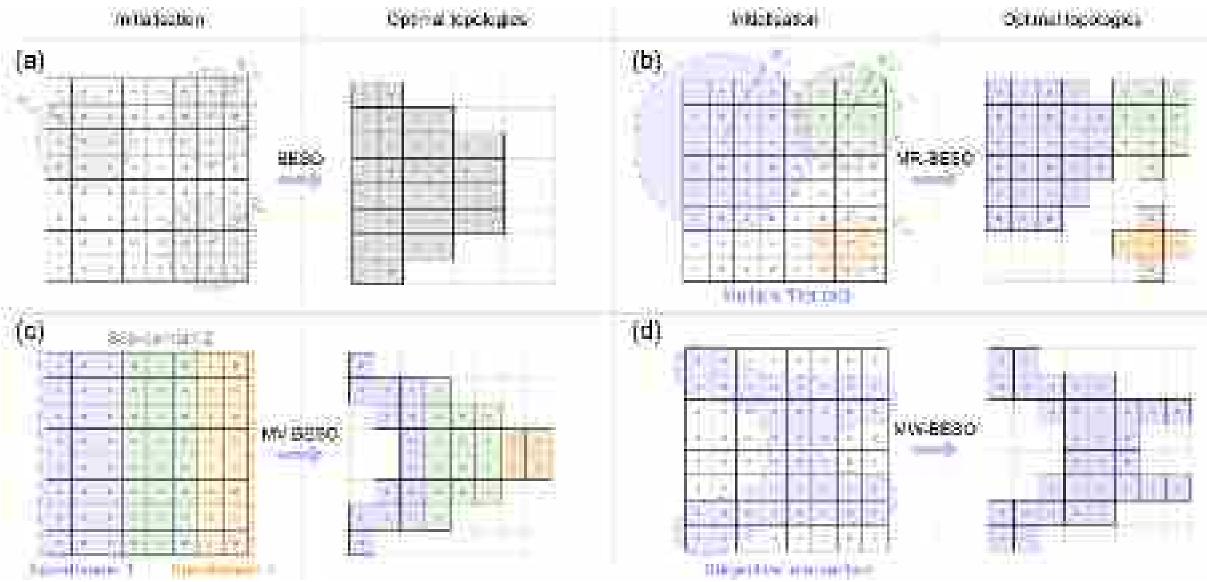

Figure 3. Comparison of the BESO method with its extensions developed based on pre-processing strategies to include subjective preferences: (a) original BESO; (b) MR-BESO; (c) MV-BESO; (d) MW-BESO [5].

The pre-processing strategies can produce efficient structural designs while including subjective preferences, as the final structural topologies are ultimately determined by the optimisation algorithm. However, there are a few limitations to this strategy. For example, as discussed in [5], MR-BESO cannot control the locations of high-stressed areas in a specific topology because the filter radius can only control the minimum sizes of structural members. As for MV-BESO and MW-BESO, although they can directly manipulate locations of high-stressed regions by altering the topologies, the use of subjective preferences may result in significant performance losses because the preferred topologies may deviate from the global optimum. Moreover, the pre-processing strategies are all performed only once, hoping to produce satisfactory designs. However, designers may wish to further refine their subjective preferences to find a better design option. Therefore, modification based on existing designs is considered a necessary process in design exploration, which is beyond the capability of the pre-processing strategies.

2.3. Post-processing strategy

The post-processing strategy involves manual processing of the optimal topologies to align with the Unity-in-Variety design principle [16]. Specifically, subjective preferences are introduced after topology optimisation is performed. Unity refers to the level of coherence that can be perceived in a design, while variety serves as a source of inspiration for designers by arousing their interest [20]. Striking a balance between unity and variety in a design can enhance the aesthetic quality and meet the design requirements of subjective preferences [21].

The manual modification involves extracting the optimised structures' contours and editing the control points to adjust the design based on subjective Gestalt principles, such as similarity, closure and continuity [16,22]. This process allows for the incorporation of subjective preferences into the optimal topology, resulting in designs that align with the desired aesthetic qualities.

In Figure 4, two pairs of optimal topologies (i.e., chairs) and their modified counterparts are reproduced from [16]. The highlighted areas demonstrate that the modified designs are edited by designers according to the continuity and similarity principles. As reported in [16], their survey claim that artificial modification can significantly improve the unity of the designs. Specifically, a majority of participants perceived the modified designs as visually more appealing. This instance exemplifies how the integration of optimal topologies with subjective preferences can further enhance structural forms to meet design requirements.

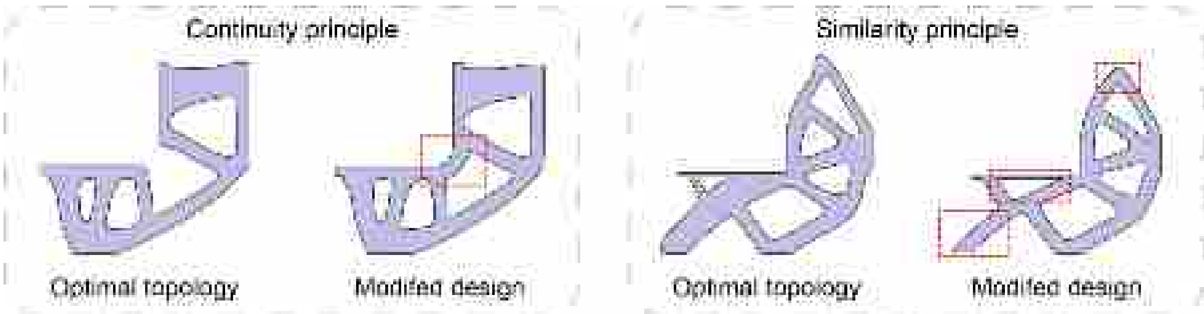

Figure 4. Two 2D chairs designed using the post-processing strategy. The highlighted areas are artificially modified based on the continuity and similarity principles. The figures are modified versions of [16].

It is worth noting that applying overly subjective intervention may be contrary to the original goal of topology optimisation, as the manual post-processing method is purely based on designers' preferences, which ignores the volume constraint and compromises structural performance. Therefore, the obtained designs may fail to fulfil objective design requirements, such as structural efficiency.

2.4. Interactive processing strategy

The two strategies above (pre-processing and post-processing) create structural designs through 'single-execution topology optimisation'. However, these strategies still face challenges in exploring satisfactory designs. In detail, while the pre-processing strategies can generate efficient structural topologies considering subjective preferences, they do not support designers in further explorations based on these results. On the other hand, the post-processing strategy requires strong artificial intervention, which ignores the volume constraint and structural performance. To address these issues, Li et al. [14] proposed an interactive topology optimisation method, SP-BESO, which considers subjective preferences (SP). This strategy introduces scoring and drawing systems that allow users to iteratively explore desired designs by alternately inputting quantified subjective preferences and performing topology optimisation. The interactive approach enables designers to balance their subjective preferences and structural performance by refining the design through an iterative process.

The SP-BESO method employs three weight-based approaches to generate preference-driven designs by affecting the ranking of elemental sensitivity numbers in BESO:

- SP-BESO uses a random perturbation technique to generate unexpected initial structural topologies (i.e., before introducing subjective preferences), enhancing the design diversity [9].
- Subjective evaluation of an existing design can be converted into weights by integrating design variables and artificial scores; these scoring weights can be used to alter the subsequent topology optimisation outcomes.
- Drawing weights are introduced that translate hand-drawn sketches into weights, guiding the next topology optimisation process to produce efficient designs similar to the inputted pattern.

It should be noted that the scoring and drawing systems can be independently executed during optimisation. Adjusting parameters, λ_e, λ_s and λ_d, can control the importance level of *structural performance*, *subjective scoring* and *drawing*, respectively. Repeatedly running the SP-BESO method allows designers to dynamically adjust subjective preferences and create improved solutions based on existing designs. However, designers may need to make refinements more than once, so the entire interactive design exploration process can be time-consuming.

Figure 5 shows a 2D chair example designed by the authors using SP-BESO. The optimisation problem is shown in Figure 5(a), with details described in [14]. For comparison purposes, the reference design (see Figure 5(b)) is obtained from the standard BESO method without considering subjective preferences. Each optimisation produces four child designs as potential design options. After optimisation, zig-zag boundaries of the child designs are smoothed to improve visual quality, assisting subjective evaluation of design options [23]. The iterative design exploration process is detailed as follows.

A preferred pattern is first drawn to connect the two supports and the backrest as the initial subjective preferences to generate the first set of solutions, as shown in Figure 5(c), where the optimisation parameters are $\lambda_e = 1$, $\lambda_s = 0$ and $\lambda_d = 0.3$. Among the four solutions shown in Figure 5(c), solutions C and D are subjectively selected as preferred designs, so they are imparted with higher scores (2 and 4); undesired solutions have lower scores (-5 and -2). From here, the optimisation parameters are updated to $\lambda_e = \lambda_s = 1$ and $\lambda_d = 0.3$ to generate a new set of designs, as shown in Figure 5(d). If one wishes to further modify the preferred design in Figure 5(d) (i.e., solution A), the drawn pattern can be modified to include the key geometrical features of solution A, with optimisation parameters adjusted to $\lambda_e = 0.8$, $\lambda_s = 0$ and $\lambda_d = 1$. Among the four solutions shown in Figure 5(d), Solution D may be selected as the final solution due to the best structural performance with the highest stiffness (i.e., the lowest C); the final 3D simulation is shown in Figure 5(f). Compared with the original BESO result (see Figure 5(b)), the final design has a 42% of performance loss (see Figure 5(e)). Nevertheless, it is still structurally efficient due to the use of topology optimisation, and the shape can fulfil subjective design requirements based on an iterative design exploration process.

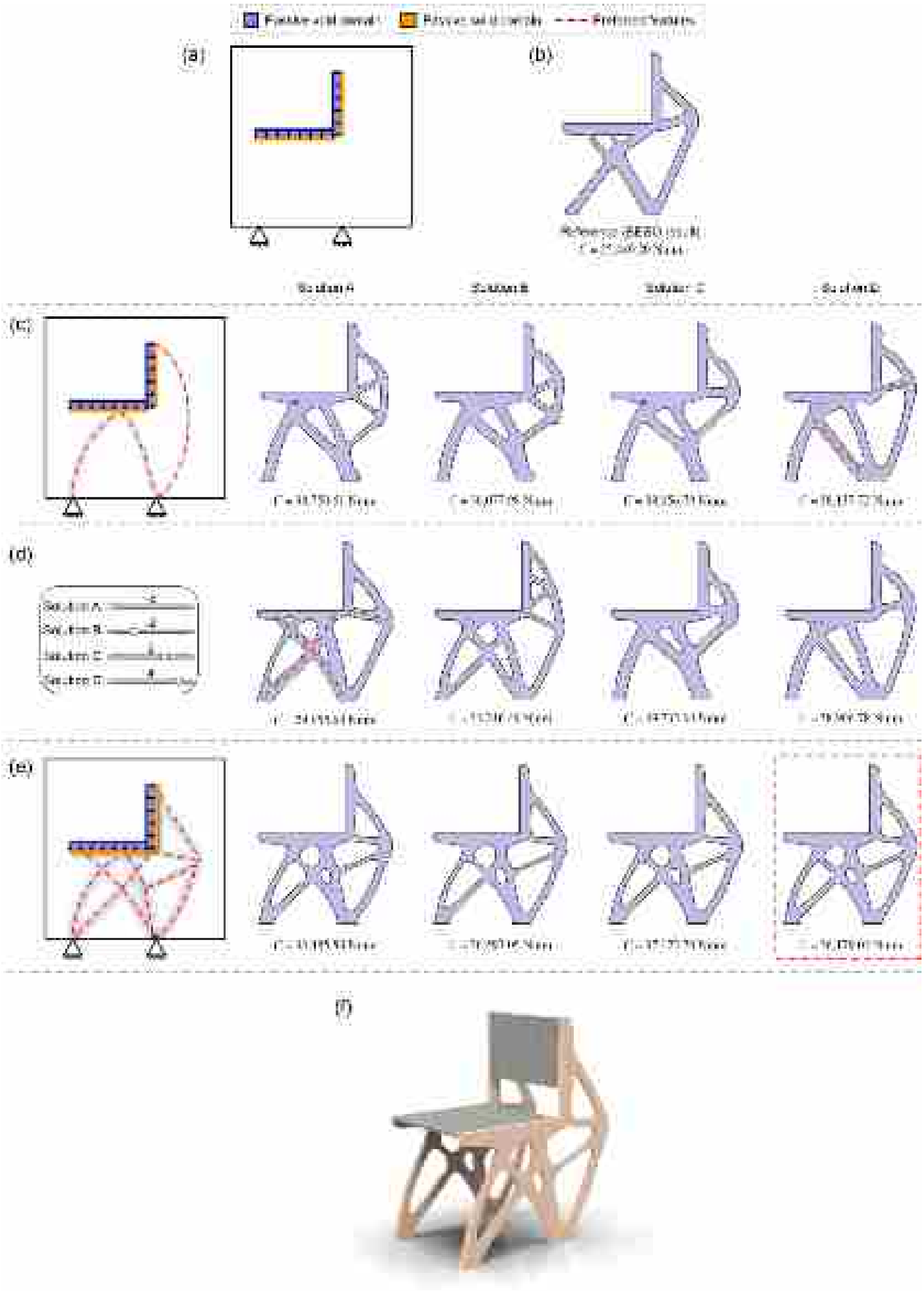

Figure 5. 2D chairs designed using the SP-BESO method: (a) loading and boundary conditions; (b) the standard BESO result; (c) child designs obtained using the drawing system ($\lambda_e = 1, \lambda_s = 0, \lambda_d = 0.3$); (d) updated designs obtained by scoring the previous child designs ($\lambda_e = \lambda_s = 1, \lambda_d = 0.3$); (e) final generation of designs ($\lambda_e = 0.8, \lambda_s = 0, \lambda_d = 1$); (f) 3D simulation of the desired design.

3. Discussion

3.1. Other topology optimisation methods

The abovementioned pre-processing and interactive processing strategies are based on the BESO method, whereas the post-processing strategy is independent of the method of topology optimisation. It is worth noting that the key advantage of using the BESO method is its simplicity in employing discrete design variables. However, the use of discrete design variables may not be sufficient to address some mathematically more complex structural design problems, such as multi-objective optimisation problems.

The pre-processing and interactive processing strategies are straightforward. They can be easily integrated into other element-based topology optimisation methods that use continuous design variables. For example, multiple filters (MR-BESO) and multiple local volume constraints (MV-BESO) can be combined with other topology optimisation methods, such as SIMP and level-set methods, to produce solutions considering subjective preferences. The same concept can be applied to MW-BESO and SP-BESO, where the weights of elements are a scalar field to penalise the sensitivity numbers independent of the underlying element-based topology optimisation method. Together, it can be understood that these potential extensions sacrifice the simplicity of the BESO method in exchange for the capability of solving complex structural design problems; future studies are needed to develop such possible extensions.

3.2. Objective functions

For certain practical applications, the overall stiffness of the structure may be less important, as the designers could be more concerned about the local performance, such as local displacement, stress and buckling. Existing topology optimisation methods that consider subjective preferences only focus on compliance minimisation (i.e., stiffness maximisation) problems. There is potential to extend these methods for optimisation of local performance while ensuring subjective preferences. The key challenge is to formulate the objective function of local performance, but mathematically possible. Furthermore, some structural designs are sensitive to minor local changes, making it crucial to carefully apply subjective interventions. Therefore, future research is needed to investigate the influence of subjective interventions in sensitive areas. Overall, there is a need for future research to consider different design objectives than just compliance minimisation to develop topology optimisation techniques that can be applied to diverse real-world scenarios while ensuring subjective preferences.

3.3. Structural complexity control

To enhance the effectiveness of pre-processing and interactive processing strategies, quantified subjective preferences can be supplemented with additional geometric constraints, similar to the structural complexity control technique [12]. For instance, the number and location of holes can be explicitly pre-defined before carrying out topology optimisation, which enables users to manage manufacturing difficulty and costs according to fabrication limitations. However, too many holes can pose significant challenges in fabrication [13]. Besides, some designers consider the number of holes a valuable aesthetic contribution as they can modify how light interacts with the structure, creating unique lighting and shadow effects that enhance the design's visual appeal.

It is worth pointing out that existing topology optimisation techniques that consider subjective preferences do not yet use geometric constraints to impact the complexity of final outcomes based on fabrication limitations or functional aesthetic requirements. Therefore, future research could explore ways to utilise geometric constraints to address diverse demands in practical applications while ensuring other subjective preferences are met.

3.4. 3D applications

Designing a structure in 3D space provides more flexibility and richer geometric details, resulting in more accurate real-world representations [24]. It should be noted that the three strategies outlined in this paper have not yet been extended to 3D cases. Addressing this goal requires overcoming three technical challenges.

The first challenge is visualisation. Specifically, accurately observing and evaluating a given 3D structure can be difficult for inexperienced designers, as it requires strong spatial awareness skills to look at many 3D geometric details. Therefore, precisely determining subjective preferences based on these observations becomes a demanding task.

The second challenge is interaction. Some manual-based interactive operations, such as drawing, struggle to work in 3D. That is because 3D structures often include numerous internal elements that cannot be directly visualised and edited from the outside. That is to say, concisely and accurately interacting with 3D structures to include specific subjective preferences can be a complex task.

The third challenge is structural performance. Subjective intervention in 3D topology optimisation may result in more significant performance losses than in 2D cases. The increased design degrees of freedom provide greater opportunities for subjective intervention to deviate from the globally optimal solution, meaning that even minor modifications may severely compromise the structural performance.

These three technical challenges require further exploration in future research, aiming to develop a practically useful 3D topology optimisation tool that can create appealing, efficient and reliable structures based on subjective preferences.

4. Conclusion

This paper presents a review of the latest topology optimisation methods considering subjective preferences. Existing methods are classified into three groups, pre-processing, post-processing and interactive processing strategies, depending on the conditions of subjective interventions in topology optimisation. The pre-processing strategies can generate diverse and competitive structural designs, but they may not be able to obtain a satisfactory solution. This is because the optimisation is performed only once, with subjective preferences specified beforehand without allowing any further refinement, leading to the hope of achieving satisfactory designs in a single attempt. The post-processing strategy involves manual modifications to the optimal structural topologies based on subjective design principles, resulting in highly preferred customised designs. However, this approach may overlook objective design requirements such as volume constraints and structural performance, potentially compromising the overall effectiveness of the optimisation. The interactive processing strategy enables designers to iteratively explore desired designs by inputting quantified subjective preferences and performing topology optimisation in alternation. This approach forms an iterative design exploration process that strikes a balance between structural performance and subjective preferences. However, refinements of subjective preferences may be made more than once, so the entire process can be time-consuming.

This paper also proposes four potential extensions of the strategies discussed above. Firstly, all existing strategies have the potential to be extended to other topology optimisation methods, expanding their applicability to other structural design problems. Secondly, extending the existing strategies to consider design objectives other than compliance minimisation may be useful for specific applications; the overall stiffness may be less important, as the designers could be more concerned about the local performance. Thirdly, incorporating geometric constraints into the existing strategies may lead to more useful solutions that can simultaneously satisfy diverse design requirements, such as fabrication limitations and aesthetic requirements. Lastly, it is highly desirable to extend existing strategies to 3D structural design problems for more realistic applications. However, the 3D extension faces challenges related to visualisation, interaction and structural performance loss, highlighting the need for further research. Undoubtedly, there is significant potential for further development of topology optimisation techniques considering subjective preferences that can be applied in real-world scenarios to create innovative, efficient and satisfactory structural designs.

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