SWARMBESO: MULTI-AGENT AND EVOLUTIONARY COMPUTATIONAL DESIGN BASED ON THE PRINCIPLES OF STRUCTURAL PERFORMANCE

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Abstract. This paper posits a design approach that integrates multi-agent generative algorithms and structural topology optimisation to design intricate, structurally efficient forms. The research proposes a connection between two dichotomous principles: architectural complexity and structural efficiency. Both multi-agent algorithms and Bi-directional evolutionary structural optimisation (BESO) (Huang and Xie 2010), are emerging techniques that have significant potential in the design of form and structure.This research proposes a structural behaviour feedback loop through encoding BESO structural rules within the logic of multi-agent algorithms. This hybridisation of topology optimisation and swarm intelligence, described here as SwarmBESO, is demonstrated through two simple structural models. The paper concludes by speculating on the potential of this approach for the design of intricate, complex structures and their potential realisation through additive manufacturing.

Keywords. Swarm Intelligence; Multi-agent; BESO (bi-directional evolutionary structural optimisation); Intricate Architectural Form; Efficient Structure.

1. Introduction

This research posits an innovative design methodology that establishes a complementary relationship between topological optimisation and behavioural generative design algorithms. The research explores and evaluates the application of topology optimisation and multi-agent algorithms in a form-finding design process. It demonstrates the process of integrating these two algorithms to establish a real-time structural feedback loop in the process of designing intricate forms. It describes a hybrid of architectural and structural behaviours through the integration of swarm systems and BESO methods.

This approach, termed swarmBESO (see figure 1), creates a negotiation between concerns of architectural design and structural engineering in a simultaneous generative approach. This is a fundamental shift from the normative sequential workflows that either inform generative approaches with structural analysis or operate sequentially to optimise the structure of complex geometries already created within generative processes. The swarmBESO algorithm is demonstrated here through two- and three-dimensional cantilevered structure examples.

The future application of swarmBESO to architectural design will enable the creation of complex, the expressive architectural form which is highly efficient in terms of material and structural performance. The complexity and intricacy of the geometry generated through this process are expected to become increasingly feasible through the rapid development of building-scale additive manufacturing approaches.

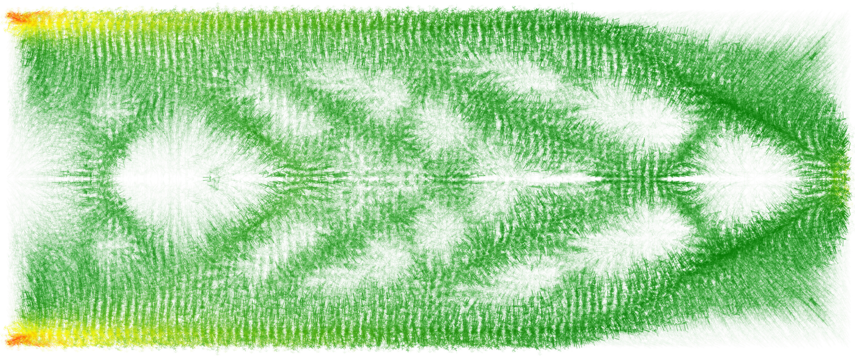

Figure 1. SwarmBESO.

2. Swarm Intelligence and Behavioral Formation

Swarm intelligence examines the emergent behavior of systems that self-organise through the interaction of autonomous agents. This behavior is evident within the natural world through systems such as flocks of birds, schooling of fish, and social insects' interaction.

The phenomena of swarm intelligence can be simulated and generated through multi-agent algorithms - a computational logic that dates to John von Neumann's work with cellular automata in the 1940s. Multi-agent algorithms operate through the local interaction of computational agents. This interaction of agents creates a self-organising behavior at the meta, or global, scale. These algorithms establish a non-linear relationship where each agent responds to the neighbouring agents without hierarchical, or top-down, control.

The development of generative design processes based on multi-agent algorithms has been emerging for twenty years within experimental architectural practices and academia. One pioneering approach, Behavioral Formation, has been developed by Roland Snooks that builds on the computational boids research of Craig Reynolds. (Reynolds 1987).

Behavioral Formation is a generative design approach that draws from swarm intelligence logic and operates through a multi-agent algorithmic process (Snooks 2014). Through this approach, the architectural intention is encoded within computation agents. The interaction of which creates a self-organised design intention and generates emergent proto-architectural form.

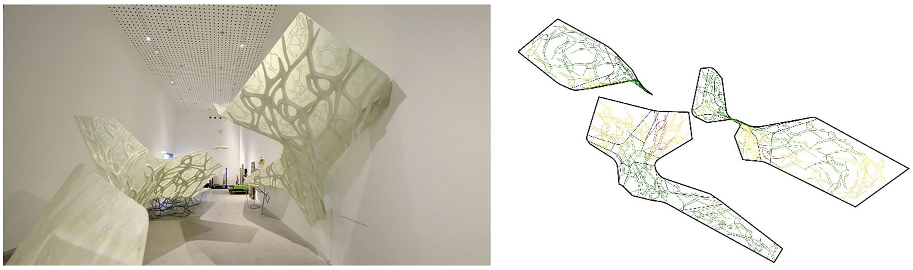

Figure 2. Composite wing by Studio Roland Snooks.

The exclusively local interaction of multi-agent systems creates self-organising behaviour at the expense of global, or meta, awareness. This global ignorance limits the capacity of multi-agent design strategies to respond to global conditions such as topology, enclosure and structure. A strategy has previously been proposed by Roland Snooks in response to this, termed *agency of structure*, which operates through a heuristic approach to local structural behaviors that respond to global structural analysis. Agency of structure "operates by iteratively testing agent-based geometry, such as a network of members or bundle of strands, using a finite element structural method. Finite element methods analyse the entire structural topology and return information pertaining to each individual node or agent (see figure 2). The agent adapts its behavior in response to this information based on heuristic structural rules designed to resist the load. Through this strategy, agents respond to the local implication of global conditions and, in doing so, re-form the global conditions, setting up a continuous feedback loop." (Snooks 2014, p131-132)

3. Bi-directional Evolutionary Structural Optimisation Method

Topology optimisation techniques have been widely used in structural fields. Conventional optimisation methods are always aimed at achieving the single purpose of maximising the structural performance. Due to the potentials for generating elegant and light-weight structures with high structural performance, topology optimisation has gained extensive attention and experienced considerable progress over the three decades. Topology optimisation aims to find an initial structural configuration which meets a predefined criterion, and occasionally it gives a design that can be completely new and innovative. Several notable topology optimisation methods have been widely developed in topology optimisation field, e.g. the homogenisation method (Bendsoe 1989; Bendsoe and Kikuchi 1988), the solid isotropic material with penalisation (SIMP) method (Bendsoe and Sigmund 1999; Bendsoe and Sigmund 2004), the evolutionary structural optimisation (ESO) (Xie and Steven 1993; Xie and Steven 1994), the bi-directional evolutionary structural optimisation (BESO) (Huang et al. 2007; Huang and Xie 2007) (see figure 3) and the level-set method (LSM) (Wang et al. 2003; Allaire et al. 2004). Among others, BESO method has been proved to be a reliable optimisation technique, which has been successfully applied in many engineering and architectural design (Zhao et al. 2018; Yan et al. 2019; Burry et al. 2005).

Figure 3. Bi-directional Evolutionary Structural Optimisation (BESO).

Although most topology optimisation techniques aim at achieving the most optimised solution, the structural layout with the highest performance may contradict the functional requirements and aesthetic designing concepts in real problematic practices. Therefore, some modification methods based on conventional topology optimisation are explored widely to solve specific application problems. In 1992, Mike Xie and Grant Steven proposed a numerical method for topology optimisation Evolutionary Structural Optimisation (ESO) (Xie and Steven 1993; Xie and Steven 1994), and later Mike Xie and Xiaodong Huang developed the Bi-directional Evolutionary Structural Optimisation (BESO). BESO method allows the material to be removed and added simultaneously. In BESO method algorithm, The initial research on BESO was conducted by (Yang et al. 1999) for stiffness optimisation. “In their study, the sensitivity numbers of the void elements are estimated through a linear extrapolation of the displacement field after the finite element analysis. Then, the solid elements with the lowest sensitivity numbers are removed from the structure, and the void elements with the highest sensitivity numbers are changed into solid elements.” (Huang and Xie 2010, p17). Two unrelated parameters determine the numbers of removed and added elements in each iteration: the rejection ratio (RR) and the inclusion ratio (IR), respectively. “In their BESO algorithm, elements with the lowest von Mises stresses are removed, and void elements near the highest von Mises stress regions are switched on as solid elements. Similarly, the numbers of elements to be removed and added are treated separately with a rejection ratio and an inclusion ratio, respectively.” (Huang and Xie 2010, p17).

4. SwarmBESO Methodology: BESO Logical Multi-agent System

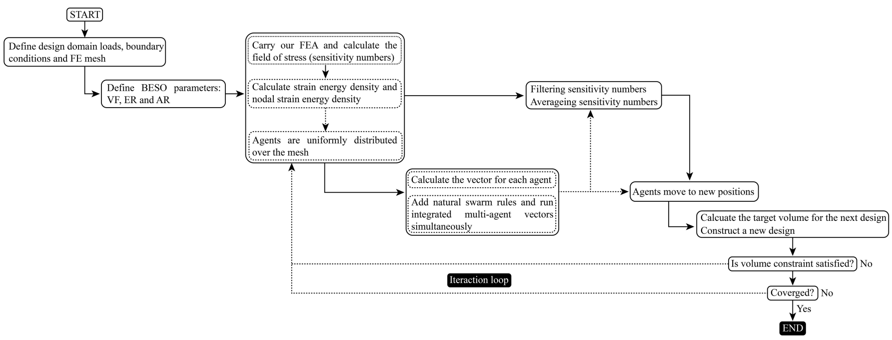

Figure 4. Flowchart of the SwarmBESO method.

The swarmBESO approach involves iterative feedback where the results of an FEA analysis drive structural behaviour within a multi-agent generative algorithm, which in turn re-forms a structural mass. Each step of the agent triggers this recursive process such that a constantly updating structural model drives every step. The multi-agent generative algorithm negotiates between these structurally driven behaviours and non-structural design behaviours, to create forms that are generated by architectural design intention while being near-optimal structural solutions (see figure 4).

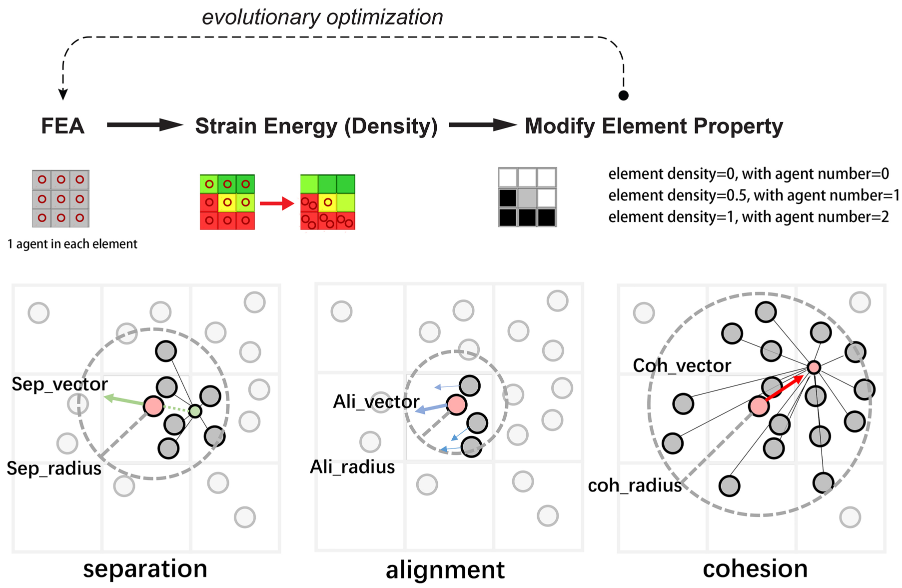

Figure 5. The logic of SwarmBESO method.

The agent number in each FEA element is connected with the relevant element material property, which means the element will be given a softer material with less Young's modulus value in the next iteration if it has fewer agents inside. As the diagram shows (see figure 5), a strain energy field is generated based on the whole structure FEA result in each iteration. Every agent can be assigned an initial velocity according to the strain energy field, and this velocity represents the structurally driven behaviour. Furthermore, some essential swarm-rule-based modifications, such as separation, alignment and cohesion, are introduced to modify the initial agent velocity. As a result, with the modified velocities, agents will make movements inside the FEA mesh and change the next FEA process's material properties.

4.1. 2D CANTILEVER

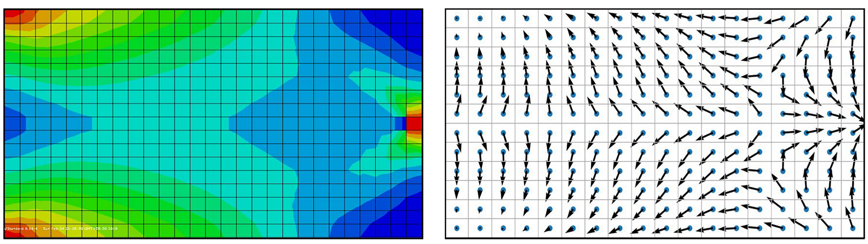

Figure 6. 2D Cantilever in FEA platform (left) and initial generated velocity field (right).

The 2D cantilever model is a classic analysis model in structural optimisation. The plate model is fixed around the left side and subjected to a concentrated load at the middle point on the right side (see left in figure 6). With swarmBESO method, the strain energy field and initial structurally driven velocity field are generated like the illustration (see right in figure 6). After several iterations, the agent can be re-located as the diagram shows (see figure 7), and this result is similar to the conventional topology optimised result.

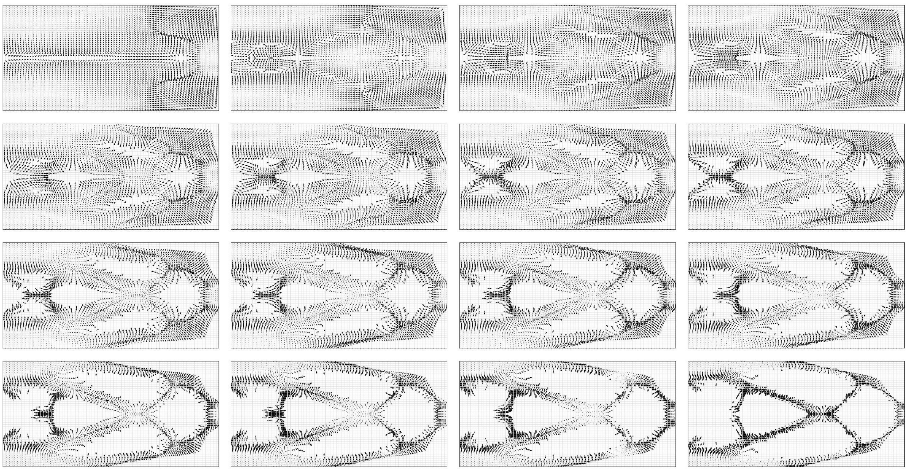

Figure 7. 2D evolutionary result.

The new method has also been tested on the 2D long beam structure (see figure 8). The colourful cloud pictures are the visualization result of analysed data in finite element method. The green figures are the normal BESO result. The multi-agent figures are the swarmBESO result, they are respectively iteration 10 (see left in figure 8) and iteration 35 (see right in figure 8). In comparison, the swarmBESO results both achieve structural performance and have more complex & diverse forms.

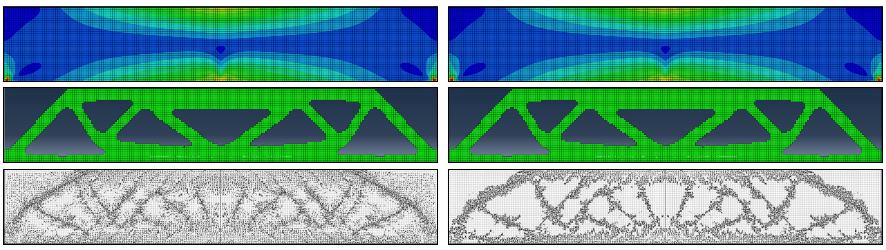

Figure 8. BESO and swarmBESO result comparison.

However, because of the single element layer, the 2D model may be faced with some local blocking during the evolution process. In the 3D model, the situation will be averted as there are multi-movement strategies for an agent to bypass the local obstacles.

4.2. 3D CANTILEVER

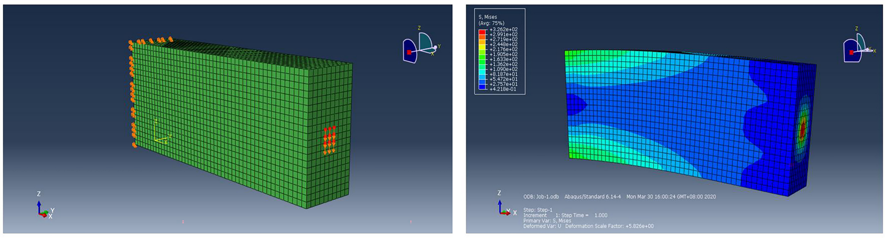

Figure 9. The 3D cantilever in FEA platform.

Initially, a simple 3D cantilever (solid element) is tested for swarmBESO algorithm in the FEA platform Abaqus (see figure 9). After setting up the boundary conditions, the finite element method analyses the entire structural surface, and return the information of the field of stress and strain energy density (SED) among the whole structure. A certain number of agents are uniformly distributed over the entire structure to represent the material distribution.

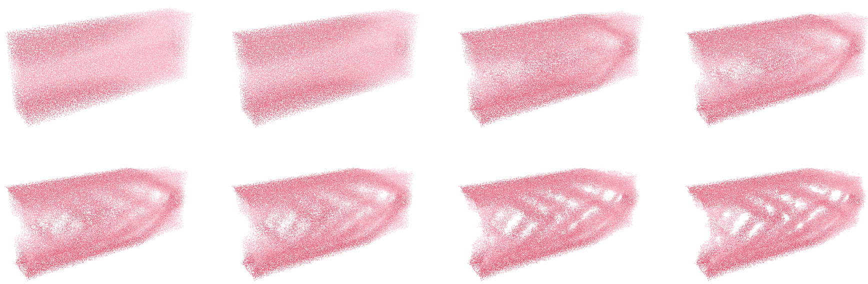

Figure 10. Real-time SED information feedback and iterations.

Based on the returned information of the field of stress and SED, the initial vector will be applied to each agent. At the same time, three basic swarm rules are applied to the agents (see figure 10).

The agent adapts its new modified behaviour in response to this integrated information of vector and starts to move to a new position. Based on the logic of BESO (Huang and Xie 2010), the material distribution will be kept updating in each loop iteration until it reaches a certain volume fraction.

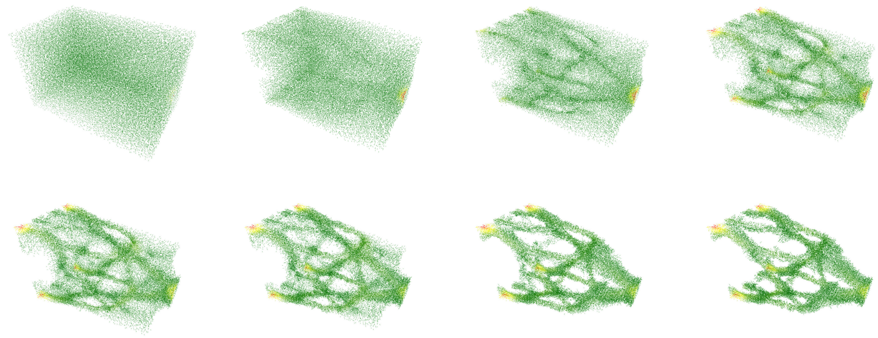

Figure 11. 3D evolutionary process.

In each step of the iteration, the information of structural performance will be returned and reviewed. The information can be analysed by checking the strain energy density distribution. Thus, the structural logic-based swarm evolutionary method is applied and tested. From the above diagram (see figure 11), it is evident that the swarmBESO generations are less than conventional topology optimisation methods. In swarmBESO, all the agents are motivated based on local rules at the same time rather than just some certain areas are changed in other traditional methods. As a result, it may be difficult for swarmBESO to find the globally optimised structure, but it can generate diverse results with similar structural performance.

5. Conclusions

The integration of multi-agent generative algorithms and structural topology optimisation creates a simultaneous process of architectural and structural generation. This approach has the potential to develop a closer working collaboration between architects and structural engineers in the early stages of design and to avoid the structural rationalisation of unfeasible architectural forms. The next steps in this research are to demonstrate the capacity of this algorithmic tool through the design of several prototypical projects and to embed the logic of additive manufacturing techniques within the swarmBESO algorithm. While the simple cantilever examples illustrated here to demonstrate the operation of swarmBESO, the real potential in this approach lies in the capacity of this algorithm to create highly complex and intricate architectural tectonics that are structurally efficient.

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