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A Comparative Study of Different Grasshopper Plugins for Topology Optimization in Architectural Design

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Abstract

Topology optimization (TO) is one of the structural optimization methods used to find the best suitable material distribution, resulting in the most efficient structure. Looking into literature, TO applications in the architectural field is still relatively limited compared to other engineering fields. In recent years, however, various computational design methodologies have acquired prominence in the architectural community. The predominant use of digital design tools during the architectural design process necessitates conducting more research on these tools. Furthermore, as new tools for applying each algorithm and method emerge, the efficiency of these tools must be evaluated. This study aims to explore and compare three available tools for implementing TO. A box is used as a case study to conduct a comparative study between the three grasshopper plugins for topology optimization: Millipede, tOpos, and Ameba. From an architectural standpoint, the potential and efficiency of the three plugins are discussed.

1. INTRODUCTION

Topology Optimization (TO) is a method used to obtain the optimal distribution of material within a design domain [1]. Topology optimization answers the main engineering question of how to place material within a domain to achieve the most efficient structure [2]. It is one of the sub-methods of structural optimization widely used in mechanical and automotive engineering. However, it has potential in the architectural field and can offer many possibilities. As economic aspects and structural stability are essential in structural engineering, optimization helps minimize resource consumption while meeting performance objectives. With the help of computational tools, topology optimization could be used to generate novel, structurally sound architectural forms [3].

The goal of this study is to present tools designed for topology optimization and make a comparison between the available grasshopper plugins for implementing TO. The research is limited to Grasshopper's topology optimization plugins: tOpos, Millipede, and Ameba. The reason behind focusing only on grasshopper plugins is that Grasshopper is a popular platform, easily accessible for students, and topology optimization plugins can be connected with other tools effortlessly to perform other tasks and studies. That is along with the availability of research comparing other commercial programs and their topology optimization capabilities.

2. TOPOLOGY OPTIMIZATION

Structural optimization can be divided into three different methods: size, shape, and topology optimization (Figure 1). Size optimization is used to find the optimal material distribution for a solid structure or the thickness of members in a discrete structure. As a result of size optimization, the optimal cross-sectional area is found by changing the dimensions of each element in the structure. In a shape optimization problem, however, the design variable is the shape, and the goal is to find the optimum shape for the design. In shape

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optimization, only the geometry of the structure's outer shell is changed without changing the elements' connections. In topology optimization, the design domain is specified and used to determine the connectivity, number, shape, and location of holes within it [1,4].

Size optimization is generally used in frame and truss structures where the goal is to find the optimal cross-sectional areas of members. Meanwhile, shape optimization aims to optimize the positions of nodes that change the geometry but does not introduce or remove elements or voids. Topology optimization, however, can introduce a new topology and add or remove elements and voids [5]. Topology optimization is generally used during the conceptual stage, while size and shape optimization are used for detailed design [6]. General practice includes a topology optimization process in the first design stages of the structure and a shape and/or size optimization to find the final design. Some studies, including Hassani et al. [7] and Yoely et al. [8] suggest methods for applying topology and shape optimization simultaneously. The main difference between topology optimization and other optimization methods is that TO generates completely new structural layouts different from typical configurations [9]. While topology optimization requires a simple initial volume only, shape and size optimization need an initial parameterized model to start the optimization procedure [5].

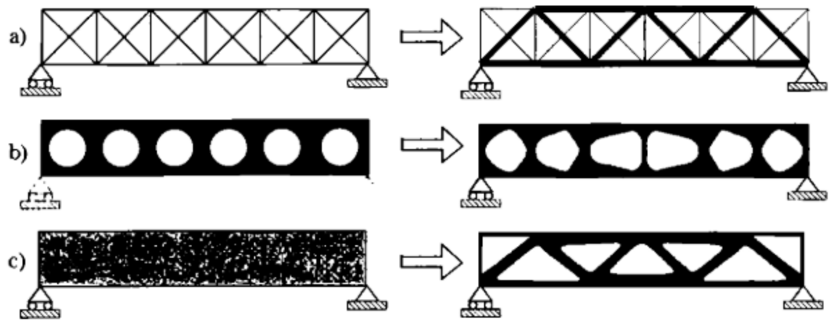


Figure 1. *Structural Optimization Categories Applied on a Truss. A) Size Optimization B) Shape Optimization C) Topology Optimization [1]*

Topology optimization is based on multiple iterations of analysis and design updates. Generally, a topology optimization process is based on an objective function that is minimized by finding the material distribution within a domain [2]. The objective function in structural topology optimization problems is primarily a compliance function. The goal of such TO problems is to reduce compliance (minimize the objective function) which results in increasing the stiffness [10]. Topology optimization distributes material within the initially specified domain based on the given loads, supports, and other design and boundary conditions. These include specific performance goals and user-specific design restrictions such as predefined voids and solid areas [3].

Homogenization could be considered the first TO method to be introduced. However, looking at the literature, it seems that the two most popular methods of TO currently are SIMP and BESO. Solid Isotropic Material with Penalization (SIMP) is a density method where the domain is divided into finite elements for which the material density is appointed based on the design variables [2]. The density ranges from 0 to 1, and a penalty method is used to eliminate these intermediate densities and turn them into discrete 0 (void) and 1 (solid) values [10]. On the other hand, Evolutionary Structural Optimization (ESO) is a discrete method in which density variables are either 0 or 1, with no intermediate densities. ESO is considered a hard-kill strategy in which elements that do not meet the criteria are removed. It has been developed into a bidirectional method (BESO) where elements can be removed and reintroduced during the process. According to Sigmund and Maute [2], BESO should be considered a discrete version of the SIMP method rather than a separate category. They both use the same sensitivity and density filters to achieve the results and vary in their update schemes, such as being discrete or continuous. As TO cannot be conducted using traditional tools, different programs and plugins are being developed for the TO process. These tools vary in their use of different TO methods and algorithms.

With the evolution of additive manufacturing, topology-optimized results have become more manufacturable. TO has been used in aircraft and mechanical engineering to produce optimal, lighter, and more efficient parts and elements such as the topology optimized jet engine bracket [11]. Product design is another field that topology optimization is being explored within. An example of that is a project where topology optimization was used for a new chair design [12]. Also, topology optimization has potential in the medical field in multiple areas, including bone replacement [13]. An example is shown in the study, which suggested using topology optimization to design a patient-specific facial bone replacement (Figure 2).

(a) *(b)* *(c)*

Figure 2. *Applications of Topology Optimization in Different Fields; (a) TO Jet Engine Bracket (b) TO Chair (c) TO Facial Bone Replacement [11-13]*

3. ARCHITECTURAL DESIGN AND TOPOLOGY OPTIMIZATION

Topology optimization is less used in the architectural field compared to other disciplines. However, with the development of computer-aided design and the focus on sustainability, TO can present an excellent tool for generating novel designs while reducing material usage [3]. The architectural design process is traditionally a linear one. The architect starts the process of producing the architectural form and geometry and then submits the work to a structural engineer [14]. Topology optimization allows architects and engineers to work together to produce architectural elements that satisfy both aesthetics and structural stability [15].

As topology optimization is a relatively new method, especially in the architectural field, the number of built projects that use topology optimization is minimal (Figure 3). Qatar National Convention Centre (QNCC) and Akutagawa West side project are among the first attempts to construct forms obtained from Topology Optimization algorithms. QNCC includes a large structure supporting its exterior canopy obtained with the help of topology optimization and had a symbolic resemblance to the famous Sidra trees of Qatar. In the Akutagawa West side project, two exterior walls were designed using topology optimization and constructed using reinforced concrete [16]. The 100 Mount Street is a project by SOM that also uses topology optimization during the design process. The core of the building is placed on the western side, which creates a need to have a structure on the eastern side to balance the building. A cross-braced exoskeleton is designed with the help of topology optimization and constructed on the eastern side [17].

(a) *(b)* *(c)*

Figure 3. *Examples of Built TO Projects; (a) Qatar National Convention Centre (b) Akutagawa West Side Project (c) 100 Mount Street [3,18,19]*

However, the interest in exploring the potential of topology optimization has increased in recent years, and recent research explores multiple approaches in different project types (Figure 4). The Unikabeton Project is an example of studying TO for concrete structures. The resulted prototype has a reduced material consumption of up to 70% compared to equivalent structures [20]. Another study explores the possibility of designing and fabricating a formwork for topologically optimized concrete slabs [21]. Gaudillière et al. [22] showcase a project in which 3D concrete printing is used to construct a topology-optimized column. Another study presents the process of designing and fabricating a concrete girder that combines 3D concrete printing, topology optimization, and post-tensioning of concrete structures [23].

(a) (b) (c) (d)

Figure 4. *Examples of Studies on the Implementation of Topology Optimization in Architecture; (a) The Unikabeton Project (b) TO Concrete Slab (c) TO Column (d) Concrete Girder [3,21-24]*

4. CASE STUDY: A BOX APPLICATION IN THE 3 GRASSHOPPER PLUGINS

A vast number of programs include a topology optimization tool within them. Some are standalone commercial programs including a built-in TO process, while others are add-ons and plugins. The environment for most of these plugins is Grasshopper. Each program and plugin is designed based on one of the well-known TO methods. The previously mentioned methods of SIMP and BESO are dominantly used as a base for the various programs. The programs vary in their ability to conduct a TO process on 2-dimensional or 3-dimensional domains. Some programs are limited to 2D or 3D, while others can work on both. Karamba3D differs from other plugins as it works on discrete elements and produces 3D discrete results rather than solid geometry. Table 1 includes a comparison between some of the available tools.

Table 1. *Comparison of available Programs for topology optimization [25-28]*

Program/ Plugin	Environment	Method	Accessibility	Dimension
Millipede	Grasshopper	SIMP*	Free	2D&3D
TopOpt	Grasshopper	SIMP	Free	2D
Topos	Grasshopper	SIMP	Free	3D
Ameba	Grasshopper	BESO	Commercial	2D&3D
Karamba3D	Grasshopper	BESO	Commercial	Discrete 3D
BESO 3D RMIT	Python	BESO	Free	2D&3D
Ansys	Stand-alone program	SIMP	Commercial	2D&3D
Altair Optistruct	Stand-alone program	SIMP	Commercial	3D
Topostruct	Stand-alone program	Homogenization	Commercial	2D&3D
Autodesk Fusion 360	Stand-alone program	SIMP	Commercial	3D
Tosca	Abaqus	SIMP/RAMP	Commercial	2D&3D

**Some resources list millipede's method as Homogenization. We lean toward the fact that the method is SIMP based on the parameters included in the plugin.*

From an accessibility perspective, commercial programs are geared more toward professional practice, while free plugins target personal users, students, and those who are exploring the method for the first time. When it comes to the environment, as grasshopper has been widely used in the architectural field recently, the plugins available in grasshopper could be preferred over others in the architectural community.

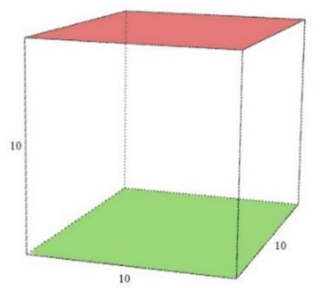
Available research comparing different TO tools is limited. SIMP and RAMP, which are two different TO methods, are compared using the same program (Abaqus) [29]. In another study, SIMP and BESO are compared using Millipede and Karamba3D [27], while Tyflopoulos and Steinert [28] compare between the commercial software programs: SolidWorks, ANSYS, and ABAQUS. No research compares the TO grasshopper plugins that produce solid 3D results.

Ameba is introduce in Zhou et al. [30] which explain how it works and provide basic implementation examples. tOpos is also introduced, and its features are discussed in multiple publications [26,31,32]. A manual introducing Millipede and its components is available online [33]. Although the grasshopper plugins are used in other research and applications, their differences cannot be apparent as the inputs differ. This research is essential because it shows and compares the plugins' efficiency by using a fixed design domain, load, support, and material properties.

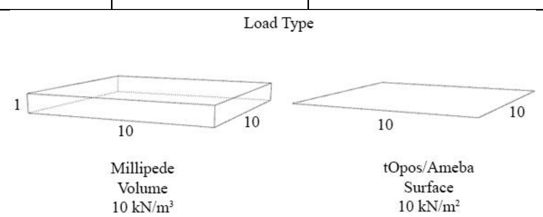
Millipede is a structural analysis and optimization plugin for Grasshopper. It can be used for 2D and 3D topology optimization along with other analysis processes. Unfortunately, Millipede is discontinued, which means it is not getting further developed and updated. tOpos, on the other hand, is a 3D Topology Optimization plugin for Grasshopper. tOpos has the option of GPU computation, which makes it faster in computation compared to Millipede. Finally, Ameba is another plugin designed explicitly as a topology optimization tool based on the BESO method. It provides optimization for both 2D and 3D domains and conduct its computation in the cloud. Although Millipede, tOpos, and Ameba are based on different TO methods, they work and produce similar results in terms of getting continuous structures rather than discrete ones.

A simple cubic box is used as a representation of architectural spaces. The top surface is identified as load and the bottom surface is identified as a support. Table 2 shows the specified domain and parameters. In addition to the fixed domain, the selected material is fixed as concrete. The material is identified in Millipede by the properties: Young's modulus (E) =48 GPa, and Poisson ratio (ν)=0.2. These properties are used for all the plugins. Although load is specified as volume in Millipede and as surface in Ameba, the sizing and load value are calculated to provide the same load for all the plugins. tOpos allows the identification of load in multiple ways, including surface and volume. Thus, a surface is used as a load for tOpos. The target volume fraction refers to the volume percentage (fraction) of the original domain that the result should reach and is set to 0.2 for the case study. Therefore, the volume of the resulted geometry should ideally not exceed one fifth of the design domain's volume.

Table 2. *Box domain and set parameters*



Dimensions (m)	Load (kN)	Target Volume Fraction
10x10x10	1000	0.20



Three different trials are conducted in each plugin. The three trials differ in the maximum iteration number, which is set to 20, 50, 100. Results of the plugins are shown in Table 3. Each result was smoothed using Dendro plugin. It is noticeable that Ameba's results are the noisiest and in need for smoothing. From a visual point of view, tOpos seemed to produce the most realistic result compared to the other plugins. Ameba produced an unevenly shaped slab supported on 6 columns that are irregularly placed and tend to be shifted towards the inner space rather than being placed at the edges of the structure. tOpos produced 8 column-like elements supporting the slab above them. They are more towards the edges of the structure, a bit tilted and branches into smaller elements towards the top. Millipede, on the other hand, produced the most untypical result with a 4 column like elements at the four corners and some diagonal supporting elements. The evolution of the structure can be seen in tOpos and Ameba's results while Millipede's results almost did not change between the 50 and 100 iterations.

Table 3. *Comparison between the results in the 3 plugins (Left: original results, Right: smoothed results)*

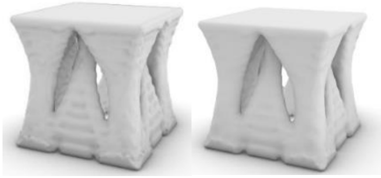
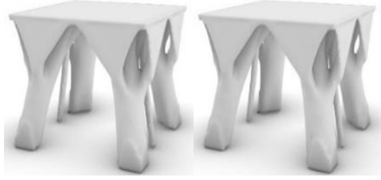
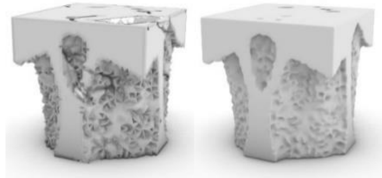
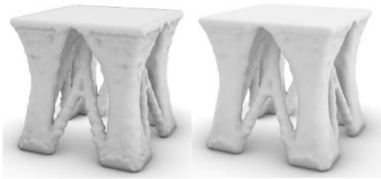
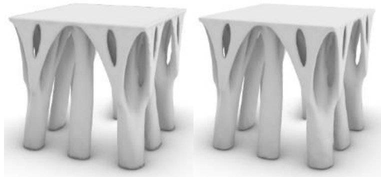
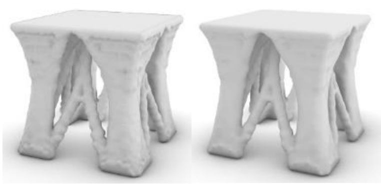
Millipede	**tOpos**	**Ameba**
		
20 iterations		
		
50 iterations		
		
100 iterations		99 iterations

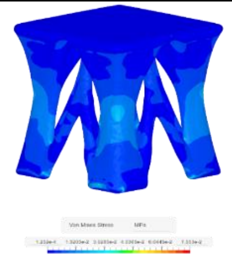
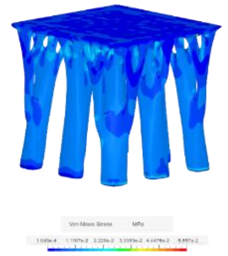
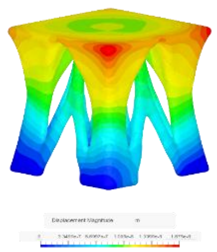
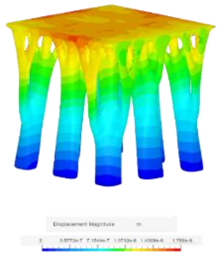
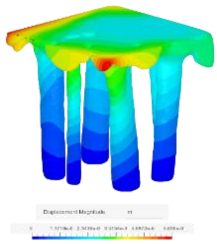
Table 4 display a comparison between the 3 plugins in optimization time, reached iterations and volume fraction. tOpos was the fastest using GPU for computation while Ameba took reasonable time computing in cloud and they both eventually achieved the target volume fraction of 0.2. Millipede took the longest and did not reach the target volume fraction. Ameba stopped at 99 iterations as it satisfied the target goal.

Table 4. *Comparison between the reached volume fraction and optimization time of each plugin*

	Max iterations:20		
	Reached iterations	Reached volume fraction	Time
Millipede	20	0.36	1 h 52 mins
tOpos	20	0.27	17 sec
Ameba	20	0.54	8 mins
	Max iterations:50		
	Reached iterations	Reached volume fraction	Time
Millipede	50	0.28	4 h 31 mins
tOpos	50	0.22	41 sec
Ameba	50	0.28	14 mins
	Max iterations:100		
	Reached iterations	Reached volume fraction	Time
Millipede	100	0.28	8 h 58 mins
tOpos	100	0.20	1 min 5 sec
Ameba	99	0.20	24 mins

Final results (using the max iterations of 100) are re-meshed and maximum Von Mises Stress and displacement are calculated using SimScale. The Von Mises stresses and displacement of the three results, which give an indication on their structural stability, are shown in Table 5. Ameba's result had the highest value in both max stress and displacement. tOpos had the least max stress value while Millipede's result had the smallest value when it comes to maximum displacement. When compared numerically, Ameba's max stress value, which is the highest between the plugins, is around 3.5 times the max stress value in tOpos. A similar result is seen in displacement values as Ameba's max displacement value is more than 3 times that of Millipede which has the lowest value.

Table 5. *Max Von Mises Stress and Displacement of results*

	Millipede	**tOpos**	**Ameba**
Von Mises Stress (MPa)			
	Max; 7.553×10^{-2}	*Max;* 5.557×10^{-2}	*Max;* 1.955×10^{-1}
Displacement (m)			
	Max; 1.675×10^{-6}	*Max;* 1.789×10^{-6}	*Max;* 5.859×10^{-6}

5. DISCUSSION

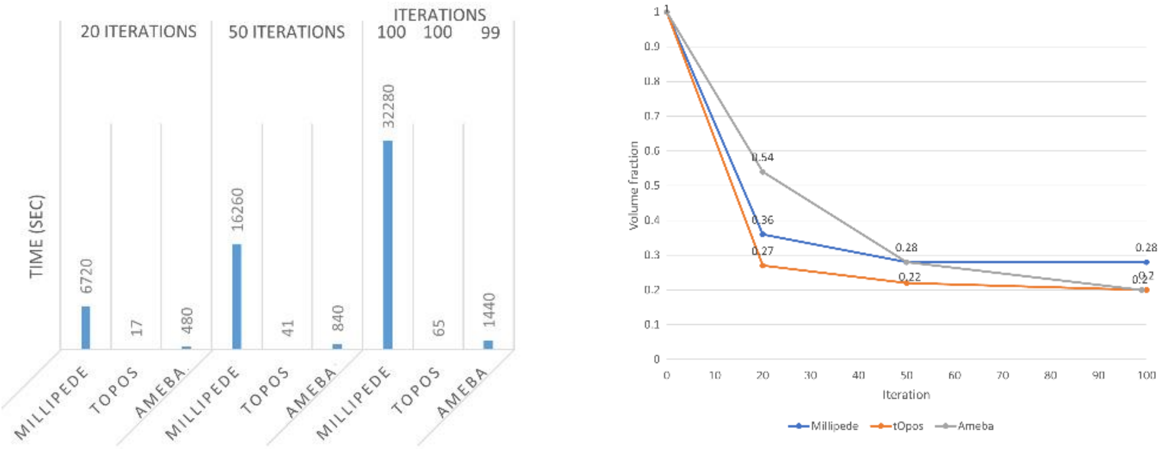
In practice, topology optimization results are generally further developed and optimized. More design development stages are required to reach a final viable design. However, this research focuses on studying and comparing grasshopper plugins for topology optimization and their ability to produce conceptual forms derived from TO. Thus, results are not further developed as it is beyond the scope of this research. Nevertheless, results can be studied and compared from different perspectives.

5.1. Optimization Time

When it comes to optimization time, Millipede took the longest out of the three plugins (Figure 5a). The number of maximum iterations is reached, although there seemed to be almost no difference between the 50 and 100 iterations results despite taking double the time. Ameba took a reasonable time to produce the final result and did stop at 99 iterations before reaching the maximum number provided. tOpos was the fastest to generate results using GPU. It is worth mentioning, however, that it is not compatible with all graphic cards. Moreover, when using GPU mode, the plugin sometimes stops during iterations without finishing and reaching the required result and other times stops working after one run. The plugin provides a reset component which often solves the issue. It also includes a CPU mode, but it takes longer than GPU mode.

5.2. Volume Fraction

The target volume fraction was reached in 100 iterations or less for Ameba and tOpos, while Millipede failed to reach the target volume fraction (Figure 5b). Moreover, the volume fraction in Millipede did not change between the 50th and 100th iteration which raises the question of whether half of the iterations were needed as the results almost did not change in the last 50 iterations. As Ameba and tOpos reached the target volume fraction, their results achieved the goal of minimizing material consumption better than Millipede's result. tOpos and Ameba's results would use nearly 30% less material than Millipede's.



(a) (b)

Figure 5. *Plugins Comparison Charts; (a) Optimization time for each trial (b) Volume fraction in relation to the number of iterations*

5.3. Structural Performance

The maximum stress and displacement values varied from one plugin to another. Ameba had the highest maximum displacement and stress value. On the other hand, Millipede had the lowest value in max displacement, while tOpos had the lowest stress value. Although Ameba and tOpos have reached the same volume fraction, their stress and displacement varied as the material distribution is different, resulting in distinct load distribution throughout the structure, thus different stress and displacement values. In general, tOpos and Millipede's results seemed more structurally stable compared to Ameba's.

5.4. Visual Standpoint

Regarding the visual aspect of the results, tOpos produced the smoothest result, while Ameba's result was highly distorted. Ameba includes a smoothing tool, and results can be edited and smoothed using other plugins, as done in this research using Dendro. Nevertheless, simple smoothing is not enough, and the results must be redrawn or at least remeshed to produce a logical outcome that can be further developed. Millipede's result was not the smoothest but significantly smoother than Ameba's. Millipede and tOpos produced almost symmetrical results, while Ameba's was asymmetrical. From an architectural point of view, results vary significantly. Ameba's placement and sizing of the six columns supporting the slab seemed somewhat random. They have different geometry, angles, and tapering from one another and are placed at varying distances from the edges of the domain. That is along with the irregular geometry of the slab itself. The eight column-like elements supporting the slab in tOpos seemed the most resembling structure of typical TO results. On the contrary, Millipede's result seemed to be the most untypical, with the four corners of the domain being solid along with having diagonal supports in the middle of each face.

6. CONCLUSION

With the advances in computer aided design and digital tools, the application of what was thought to be complex methods such as TO becomes easier and accessible for non-experts. However, the efficiency and possibilities of these tools need to be explored. This research investigated the three grasshopper plugins in which different TO results were generated. Looking at all the factors, Millipede was the weakest plugin. It took long hours to conduct each trial and failed to achieve the target volume fraction despite the long computation time. On the other hand, Ameba took reasonable time compared to millipede and did reach the target volume fraction. However, for a commercial plugin, one would expect a finer, smoother raw result. tOpos was the fastest and reached the required volume fraction while producing the smoothest results. If GPU mode works, tOpos seems to be the most suitable plugin as multiple different options and parameters can be tested quickly.

Further research can include more complex case studies and explore other details and options for each plugin. Also, the grasshopper plugins and other available tools can be compared to further study their feasibility.

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