The Eleventh International Conference on
Engineering Computational Technology
23–25 August, 2022 | Montpellier, France

Proceedings of the Eleventh International Conference on
Engineering Computational Technology
Edited by B.H.V. Topping and P. Iványi
Civil-Comp Conferences, Volume 2, Paper 4.4
Civil-Comp Press, Edinburgh, United Kingdom, 2022, doi: 10.4203/ccc.2.4.4

Enforcing Drainable Geometries in Topology Optimization for Cleanability

M. Langelaar and R.J.P. Giele

Faculty of Mechanical Engineering,
Delft University of Technology
Delft, the Netherlands

Abstract

This paper presents a novel method to ensure that designs generated by topology optimization have the property that fluids can be drained from them. This is a crucial aspect in design for cleanability, which is important in e.g. food, health, space and high-tech industries. To ensure cleanliness, stagnant fluids remaining from cleaning operations are to be avoided rigorously. Inspired by geometric constraints developed for overhang angle control in additive manufacturing, a filter procedure is proposed that ensures that generated designs fulfil the drainability requirement. Its effectiveness is demonstrated by several numerical examples, including an industrial design case.

Keywords: topology optimization, cleanability, drainability, hygienic design.

1 Introduction

For many engineering designs an important functional requirement is that parts should allow for cleaning. Cleanliness is crucial in e.g. the food processing industry, equipment for healthcare, semiconductor fabrication equipment operating in cleanroom environments, space instruments etc. The extent to which a part can be cleaned depends directly on its geometry. This has various aspects, related to the considered cleaning scenario. Common cleaning procedures involve spraying or soaking of the part in cleaning liquids. Within such a scenario, the focus of this paper is on a particular geometric aspect namely, whether the part, in a given orientation, allows for complete unassisted draining of all cleaning liquid, as remaining stagnant liquids can lead to fouling and contamination. Here, depending on the liquid and the surface properties, a certain critical *run-off angle* should be considered to guarantee the flow of the cleaning liquid under gravity. In the food industry, a typical minimum run-off angle used for drainable design is 10 degrees with the horizontal.

In a traditional manual design process, considering drainability and this critical run-off angle is relatively straightforward. However, this is different when designers aspire to use computational design methods such as topology optimization [1]. From our investigations, presently a method to enforce that the geometry resulting from a topology optimization is drainable is lacking. This forms a barrier for the use of topology optimization in the mentioned application fields, where cleanability is an important design requirement. Making manual design modifications for cleanability after optimization typically destroys the optimality of the design. Therefore, in order to give these industries access to the benefits of topology optimization, it is necessary to develop methods to consider cleanability aspects such as drainability as an integral part of the optimization process.

The approach to ensure drainability within topology optimization presented in this paper takes inspiration from filtering approaches developed for controlling critical overhang angles of additively manufactured parts [2]. Also there, control of certain surface angles is required, but an essential difference is that the relevant angles are significantly smaller for drainage control. Recently a method to address powder evacuation from printed parts was proposed [3], which has similarities with drainability requirements. However in that study, it was also found that achieving small angles is challenging. To enable realistic run-off angles, we therefore introduce a local refinement step in our method.

2 Methods

The classical and widely used density-based topology optimization approach [1] utilizing a regular finite element mesh is taken as the basis for the method. To strictly enforce the drainability requirement in every design iteration, it is effective to implement it as a filter as opposed to a constraint. This *drainability filter* serves to transform a given input density field into a drainable one. Assuming gravity acting vertically downward, void elements in each horizontal layer of the mesh must connect to voids in the layer below in order to allow draining of fluids. Furthermore, the angle of this connection should not drop below the minimum run-off angle.

This concept can be implemented in a filter process that transforms the input density field in a layer-by-layer manner from base to top. Voids that cannot be drained are filled with material, and after processing all layers a fully drainable design is obtained. Note the similarity with overhang control filters (e.g. [2]) with roles of solid and void reversed. To handle the shallow angles involved in drainabilty control, we furthermore introduce a vertical element refinement scheme to disconnect the angle from the native mesh. This refinement only concerns the density field, and does not affect the finite element mesh. It allows imposing very shallow run-off angles with sub-element resolution, as illustrated for a small 2D example in Figure 1. An analogous approach is followed in the 3D setting.

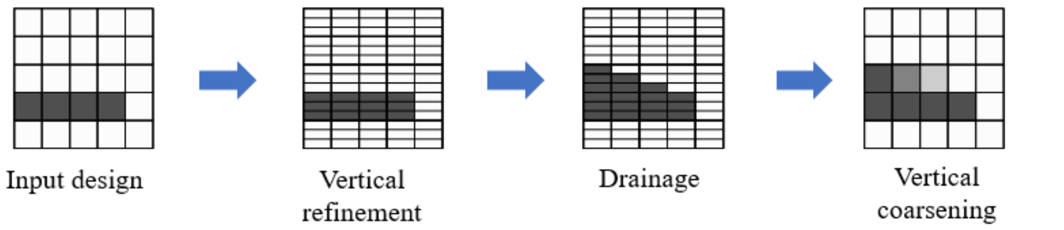

Figure 1: Schematic illustration of the use of vertical refinement and coarsening to enable shallow run-off angles in the drainability filter.

To generalize the filter, we also include the option to define an arbitrary draining direction, to consider the optimization of parts under a specific orientation. This is achieved by mapping density fields to a new grid, on which the drainability operation is performed. The adapted, drainable design is subsequently mapped back to the original mesh. In addition, the commonly used density filtering and Heaviside projection steps are added to the full filter process to control minimum lengthscale and boundary contrast in density-based topology optimization. The full chain of process steps is depicted in Figure 2. All operations can be defined as continuously differentiable mathematical operations, and thus consistent sensitivity analysis can be performed. For further details on this, the reader is referred to [4].

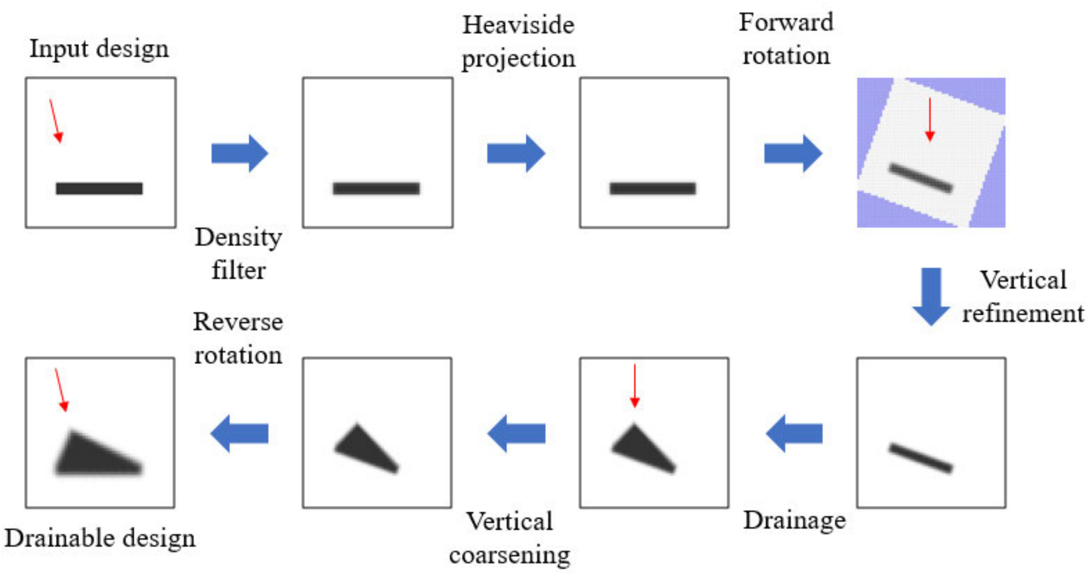

Figure 2: Full generalized drainability filter process flow for arbitrary part orientations. The red arrow indicates the relative direction of gravity.

3 Results

Using a standard compliance minimization problem under volume constraint, the topology optimization is performed using the MMA optimizer. In this section we concentrate on the most pertinent results, for a full specification of numerical parameter values, we again refer to [4]. First we present results for a basic 2D problem depicted in Figure 3(a) to illustrate and verify the functionality of the proposed drainability filter. The design obtained without drainability considerations is shown in Figure 3(b) and serves as a reference to indicate the changes induced by the new filter. Figures 3(c) and (d) show designs obtained with the drainability filter included, for two different part orientations relative to the gravity direction shown in red. A run-off angle of 11 degrees was applied. Indeed the obtained designs satisfy this requirement. It can be seen that drainability has a strong impact on the obtained design, and that internal enclosed voids are systematically removed from the solution. Under the assumption that cleaning fluids can collect in voids, all voids must be drainable, which leads to this effect. Depending on the manufacturing context, this may or may not be desirable.

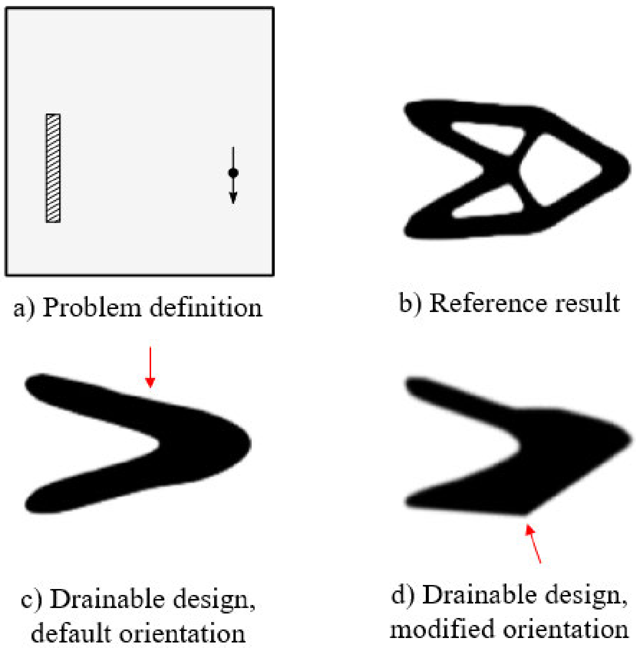

Figure 3: Definition and results of a 2D test problem, using a volume constraint of 15%. The red arrow indicates the gravity direction.

The real use cases of the proposed drainability filter involve 3D geometries. To illustrate the applicability of the approach, an indicative design case inspired on a component from industrial food processing equipment is considered. Figure 4(a) depicts the design domain for this problem (transparent blue), with loaded solid areas shown in red and displacement constraints applied to the gray regions. The specific details of this problem cannot be disclosed due to confidentiality, but to demonstrate the applicability of the filter these are also not relevant. Drainability in the negative *z*-

direction is considered with a run-off angle of again 11 degrees, and in addition for printability an overhang filter [2] is applied for a build direction aligned with the positive x-direction and an overhang angle of 45 degrees. A mesh consisting of approximately 7 million hexahedral elements was used.

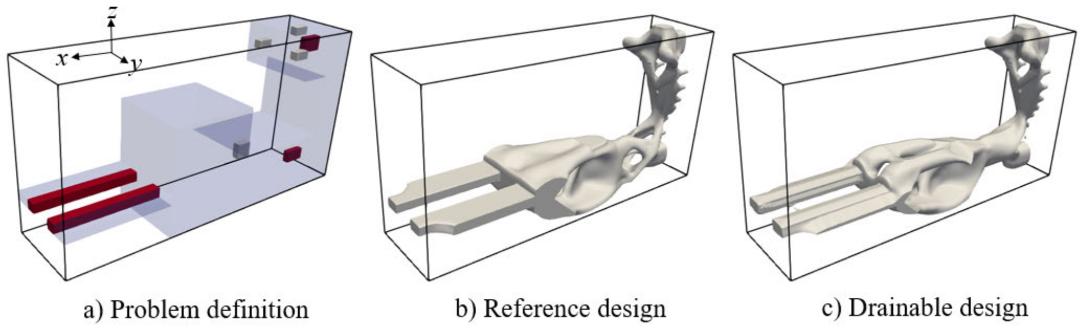

Figure 4: Definition and results of a 3D application problem. Red areas are solid non-design domains. Drainability in negative z-direction and printability in positive x-direction is considered.

Differences between reference and drainable design are less drastic in this case, but still significant. This is best seen in the close-up view presented in Figure 5. The reference design would still require manual modifications to become drainable (with consequences for its compliance and/or mass) while the drainability filter directly ensures a fully drainable result that meets all specifications. Nevertheless, in terms of structural performance and mass, the (un-modified) non-drainable reference design and the design in Figure 4(c) showed virtually equal performance.

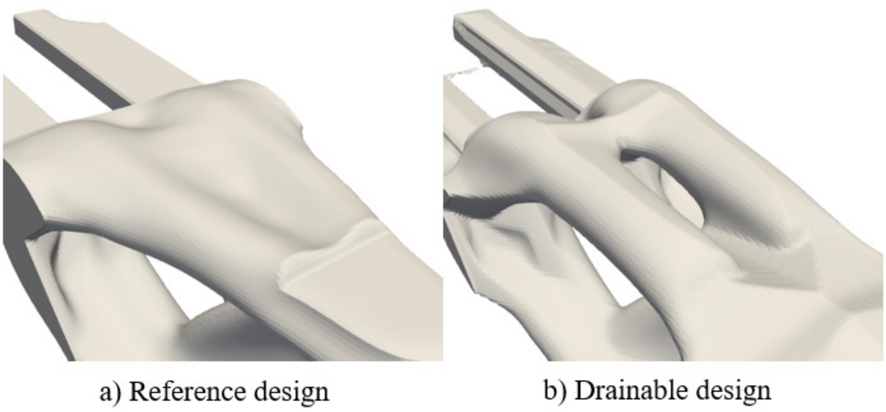

Figure 5: Close-up view of the designs obtained for the 3D application problem.

4 Conclusions and Contributions

Cleanliness is a key requirement across many industries, ranging from food processing and healthcare to high-tech and space. To help provide the full advantages of topology optimization in these fields, this paper presents a procedure to ensure drainability of cleaning fluids from the optimized components. Formulation as a filter ensures rigorous enforcement of the drainability requirement in all design iterations. Local density refinement within the filter allows for shallow run-off angles, and arbitrary part orientations can be considered. Full differentiability ensures consistent sensitivities for use with gradient-based optimization methods. Numerical examples demonstrate the effectiveness and applicability of the proposed drainability filter to industrially relevant 3D cases. Furthermore, it was found that the filter can be readily combined with control measures for overhang angles in additive manufacturing.

Drainability is an important requirement, but forms only the beginning. Future research must focus on additional aspects of design for cleanability. This includes the requirement to access all relevant surfaces when cleaning part with water jets.

Acknowledgements

This publication is part of the project RECIPE with project number 17977 of the research programme HTSM which is financially supported by the Dutch Research Council (NWO). The authors also thank Krister Svanberg for providing the MMA implementation.

References

[1] M.P. Bendsoe, O. Sigmund. “Topology optimization: theory, methods, and applications”. Springer Science & Business Media, 2003.

[2] M. Langelaar, “An additive manufacturing filter for topology optimization of print-ready designs”. Structural and Multidisciplinary Optimization 55(3), 871–883, 2017. DOI 10.1007/s00158-016-1522-2

[3] A.T. Gaynor, T.E. Johnson. “Eliminating occluded voids in additive manufacturing design via a projection-based topology optimization scheme”. Additive Manufacturing 33, 101149, 2020. DOI 10.1016/j.addma.2020.101149

[4] R.J.P. Giele, F. van Keulen, M. Langelaar. “Design for drainability in density-based topology optimization”. Structural and Multidisciplinary Optimization, accepted, 2022.