

3-D Visualization In Environmental Engineering Design Courses: If The Design Fits, Print It!

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Introduction

Most undergraduate ABET accredited environmental engineering programs have design experiences embedded in a number of courses, and typically have a course that includes a major design experience to comply with ABET Criterion V (see <http://www.abet.org/accreditation>). Designs are created to perform a function that satisfies an objective and they often result in objects that have a specified form, created by the designer. Environmental engineering examples range from a small orifice that inducts air into a water stream to a large anaerobic digester. Most environmental engineering designs are large scale, akin to the digester. Years of assessment in our capstone design course revealed that many students preferred to design large scale treatment works, but they also wanted to create a hands-on visual aid, model, or prototype of their design. Lack of a hands-on experience left numerous students dissatisfied at the end of the course, which has been a persistent shortcoming (see Ref. 1). Three dimensional (3D) printing was introduced in 2013 to address this shortcoming. This paper describes how engineering graphics software and 3D printing have been used by students to create 3D visual aids or scale models of environmental engineering projects in a one semester capstone design course. Obstacles specific to environmental engineering, including scale of the design and selection of engineering graphics software packages are discussed. Assessment of 3D printing in our capstone design course is evaluated.

Background

3D printers allow electronic source files to be converted into three dimensional objects. Most 3D printers convert stereolithography files (stl files) into objects by forming layers of plastic from the bottom to the top, which is known as additive manufacturing.² Until recently, 3D printing was used primarily by engineers for rapid prototyping. According to Kolitsky,³ 3D printing technology growth will result in widespread use in two to three years and it may become a disruptive technology in the manufacturing sector (see Ref. 4). Indeed, k-12 educators have been trained on the use of 3D printing to enhance their grasp of Next Generation Science Standards⁵ and 3D printing has been used by students in grade school.³ Use of prototyping in engineering design courses is becoming commonplace because it reinforces students' learning experience and 3D printing can accomplish this with "relative convenience."² Implementation of 3D printing has been reported to support constructivist learning theories by transforming students into creative critical thinkers.³ Although there are significant differences between 3D printing and full scale construction, 3D printing reinforces consideration for constructability, which has been noted as a common weakness among engineering graduates for quite some time.⁶

Approach

Our environmental engineering capstone design course entitled, "Advanced Environmental Engineering Design," is taken in the last term and is comprised of 40 meetings with approximately 60 contact hours. Students are introduced to a range of design experiences that

include defining the project scope, identifying design constraints, comparing alternatives, development of plans and specifications, engineering economics, and project management. Students select design projects from a list and many are drawn from current Army engineering problems. Students in three to four person teams examine projects through the feasibility and concept design phases to evolve and develop concepts that are not only technically feasible but economically, culturally, socially and politically acceptable. Course projects require literature searches and regulatory investigations. The technical nature of projects includes biological, chemical, mass transfer, and physical processes studied by the students in previous courses. A lesson on design heuristics is included to facilitate brain storming sessions. The use of decision models to evaluate alternatives is required. Students also analyze the carbon footprint of potential courses of action and use this information in their decision models. In addition, all projects include design of alternative energy systems that reduce fossil fuel requirements. Communication skills are reinforced throughout the course with students briefing (in-progress review, IPR) regularly on term project developments. The IPR process is intended to facilitate student discovery through peer-to-peer observation and investigation as well as instructor input. Both written and oral presentations are graded on style and content.

In our program, stl files are created with SolidWorks (Dassault Systèmes, Waltham, MA), which is a three dimensional computer aided design (CAD) software package. 3D printing is accomplished with a Stratasys (Eden Prairie, MN) Dimension 1200es printer, which has a build size of 254 x 254 x 305 mm (10 x 10 x 12 in.) and layer thickness of 0.254 mm (0.010 in.). CatalystEX software (Stratasys) is used to provide the interface between SolidWorks and the 3D printer. Build times have ranged from approximately 6 to 48 hours.

Students are not required to take a course on engineering drawing or CAD because of the limited number of courses offered in the major (17). Consequently, these topics are embedded in several courses. We employ a two-prong approach as follows. Students are introduced in one, one hour, instructional period (one lesson) to 3D engineering drawing with SketchUp (Google, Mountain View, CA) in “Environmental Science for Engineers and Scientists,” which is an ABET course typically taken during fall semester of junior year. Students experience an additional lesson of SketchUp in “Physical and Chemical Treatment,” typically taken during spring semester of junior year. Students use SketchUp for homework and course projects in both of these courses. We introduce more advanced engineering drawings with more detail and precision using the SolidWorks drawing package during the senior year. Seven lessons on SolidWorks has been incorporated into “Advanced Environmental Engineering Design,” where all students learn and apply basic concepts by creating a rudimentary sedimentation basin (Figure 1(a)). Major foci, here, include making parts, assemblies, and engineering drawings. Students can also take “Computer Aided Design,” as an elective, which is offered by our mechanical engineering program.

Results

A list of course projects completed by students in “Advanced Environmental Engineering Design,” since 3D printing was established in 2013 is provided in Table 1. Some of the projects were not converted into plastic 3D visual aids because these projects were not suitable for 3D printing. The instructor advised students on projects that were expected to be suitable for 3D

printing at the start of the semester. Subsequently, some students used this information as a criterion when selecting projects. In addition, 3D printouts of some designs were generated from selected components and not the entire system. For example, the printout from the “Target Hill Irrigation and Power System” was of a hydroelectric generator.

Table 1. Design Projects in “Advanced Environmental Engineering Design” since 2013. Projects that were converted into plastic 3D visual aids are identified along with a corresponding figure.

| Project Topic | 3D Printout | Figure |
|---|-------------|--------|
| Multi-Barrier Single Unit Water Purification System | √ | 3 |
| Composter for FOB Fenty, Afghanistan | √ | 4 |
| Surface Water Treatment System for a Small Developing Village | | |
| Solar Powered Thermoelectric Water Cooler | | |
| Target Hill Irrigation and Power System | √ | |
| Rainwater Collection System to Supplement Drinking Water for Honduran Orphanage | | |
| Conversion of Waste into Biochar for Energy Production | √ | |
| Sustainable Snowmaking at the Victor Constant Ski Slope | | |
| Gates Challenge Latrine | √ | 5 |
| Stormwater Collection and Irrigation System | √ | |
| Biodigester for Military Working Dog Facility | √ | |
| Generator Waste Heat Capture | √ | |

All students are introduced to SolidWorks by constructing a simplified version of rectangular sedimentation basin (Figure 1(a)). This rudimentary tank, which is based on typical dimensions, includes a baffled-wall entrance and effluent launders with V-notch weirs. Once the students have completed this in-class project, they must each complete an additional drawing as a homework assignment (see Figure 1(b) and Figure 2). Students are given the option to replicate selected drawings in their texts and other objects that are authorized by the instructor. The sedimentation basin in Figure 1(b) is an example of the drawing homework that was produced by a student with previous CAD experience from high school (not the SolidWorks program). In this case, the student’s drawing more closely replicated an example from the textbook by adding a second baffle plate to the entrance, a sloped-floor with chain and flight sludge removal system, and a more advanced weir system for the effluent. This figure illustrates that skills developed from other engineering drawing packages can be applied in SolidWorks. In addition, we give all students the basic tools to make simple engineering drawings and many can apply their baseline knowledge and creative talents to build very elaborate, detailed, and accurate models. All student design groups use SolidWorks to create engineering drawings of their design projects (see Figures 3-5 for 3D examples).

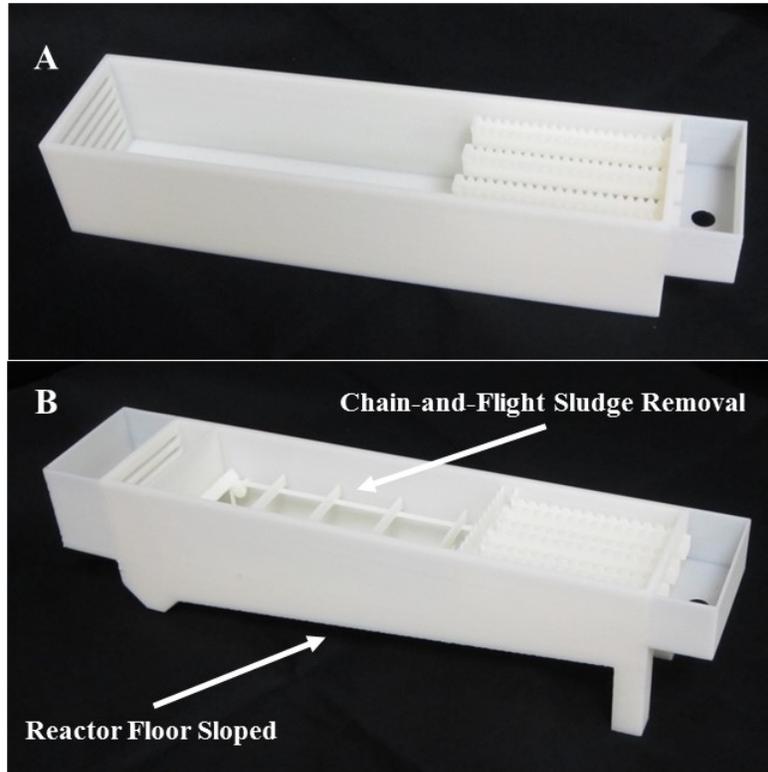


Figure 1: Sedimentation Basin. (A) All students create this basin as they learn the SolidWorks program. (B) This more advanced sedimentation basin illustrates the level of detail and realism students can produce in a short period of time. The modifications include entrance and weir baffles, chain-and-flight sludge removal system, and the reactor floor sloped.

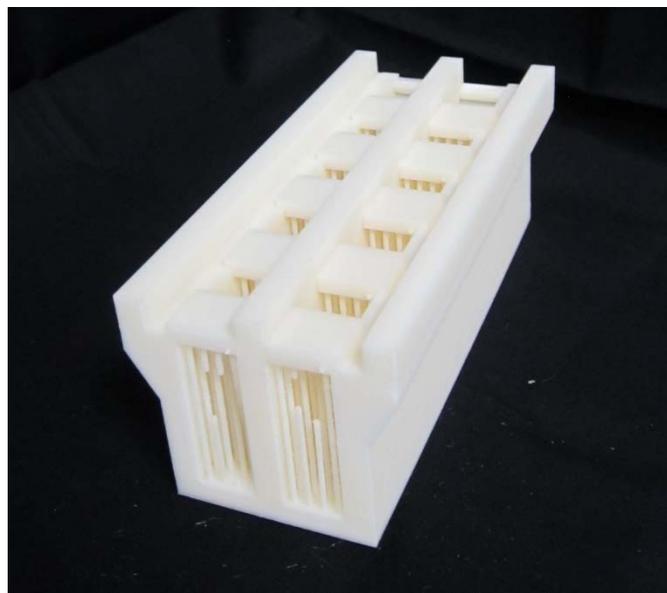


Figure 2. This UV disinfection reactor was drawn as part of a homework assignment in the capstone design course. Students select figures from their text to recreate in SolidWorks. The individual structures (vertical tubes) that model the UV lamps are broken in the front part of this 3D prototype. This highlights the shortcoming associated with maintaining the integrity of the real-world scale with the scale used during the 3D print process.

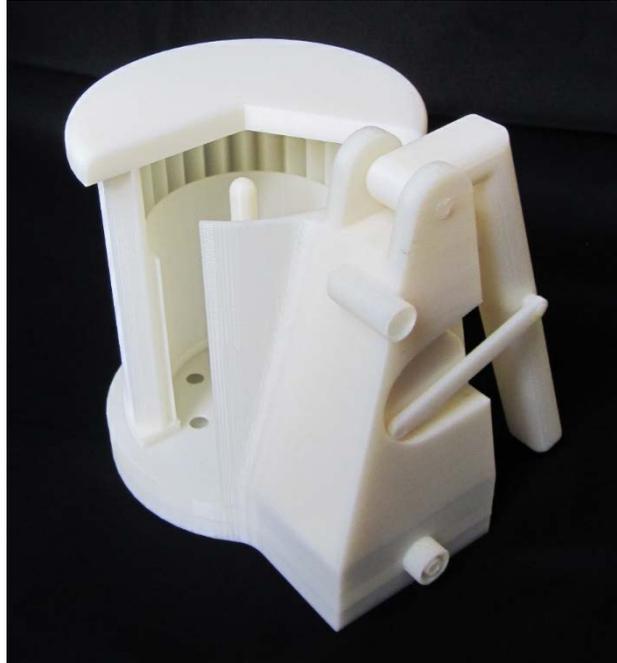


Figure 3. A multiple-barrier hand-held water treatment device that provides protection against a range of microorganisms including viruses, bacteria, and protozoa. Hand power conveys the water through the device and provides electricity to operate a UV disinfection system.



Figure 4. This solar-powered compost vessel was designed to improve solid waste management practices at remote Army bases such as forward operating bases (FOBs). This design shows utilization of typical (on FOBs) metal shipping containers. The compostable solid waste would be added through a hatch on the top (not shown). The mixing mechanism shown would be solar-powered and operated like current enclosed-vessel windrows operated in northern climates. The plenum floor would allow dewatering to occur and the mixing system would move the composted material to the end of the raised floor to be hauled off-site. This vessel could be incorporated in the perimeter defense of the remote facility. The composted material could then be used as a soil amendment by local communities.



Figure 5: This community based latrine design shows the external view of the proposed solution. The issue of scale is highlighted as the thickness of the railing supports must be scaled properly or they will be too fragile and are higher risk for breaking.

Figures 6 and 7 present projects that were completed by students as part of a one semester independent study.

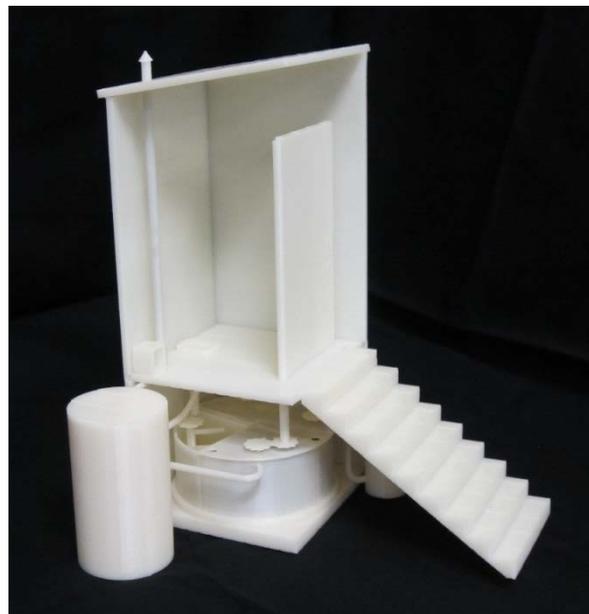


Figure 6. This composting toilet design was in response to a Gates Foundation Challenge. This design shows a perspective to highlight the novel modifications to current composting toilet designs. The external tank (bottom left) is part of the urine separation system. The composting carousel (bottom) is designed to collect the solids in the system and operate as a sequencing batch reactor (SBR). Unique to this design is that the SBR is mixed every time the door is open and shut.



Figure 7: Latrine-based Biogas System. This design (top) was created to communicate the components and concept of a biogas digester build at a rural school in western Uganda. The horizontal plane (x-y plane) shows the relevant perspective of the ground surface to delineate the aboveground and subsurface components of the system. The final constructed latrine (bottom) is operational and produces biogas used to fuel the cook stove in the school kitchen. The combination of 2D images and 3D models has been used several times to describe this outreach project completed as part of a student research project.

Assessment

Although 3D printing is common in engineering disciplines and even grammar schools, the scale and nature of some engineering processes may be limiting the integration of 3D printing in some academic programs. For example, build space was a limiting factor in fabrication of electric go-kart parts in a mechanical engineering design course.⁷ Often, environmental engineering designs are characterized by large reactor vessels and relatively small pipes, fixtures, and instrumentation. Scaling down dimensions to fit within the build envelop of our printer has resulted in some components with dimensions that were too thin and subject to breakage. Figure 2 highlights this problem as the vertical tubes were designed at the appropriate scale required in the real-world construction. However, these tubes were so small that they were fragile and broke easily when handled. We developed a method (see Appendix) for adjusting component dimensions to lower failure incidents. Based on experience, we determined that a minimum dimension of 0.1” would substantially reduce breakage of components. Naturally, changing dimensions converts a scale-model into a less representative “visual aid”. However, we found that visual aids can serve an effective means for students to communicate their designs to stakeholders.

SolidWorks was selected as our engineering graphics package because it is well suited for creating stl files for 3D printing and it was already used by our university’s mechanical engineering program in several of their courses. We have found that SolidWorks is a powerful tool for design of small environmental engineering parts and devices such as a handheld water purifier (Figure 3). However, we have had limited success using the pipe routing application in SolidWorks for design of environmental engineering process treatment trains. We are currently investigating other software options (e.g. AutoCAD Plant 3D) that may bridge the gap between these different design forms.

Our students present the results of their designs during Projects Day, which is a campus wide event used to showcase student work (similar to a poster session at a conference). Because of the significant number of design requirements in the capstone course, students are often rushing to complete their projects and get them printed in 3D. Also, because build time can be on the order of days, mistakes discovered after printing has commenced have resulted in undesirable products in some cases. Our instructors and staff attempt to mitigate this issue by carefully reviewing student designs before printing. Paudel² reported similar issues regarding hasty printing of student projects at the end of the semester.

Assessment and evaluation of the capstone course student outcome entitled, “Create technical solutions to complex, open-ended environmental engineering design problems” is completed each year as part of our annual course assessment report (Table 2). This outcome assessment includes both direct and indirect measures. Student performance on this outcome, for 3 years before and after implementation of 3D printing, is presented in Table 2. The results suggest that the influence of 3D printing, on attainment of the outcome, was not apparent because the data were not significantly changed ($P < 0.3877$). In addition, final design report grades (Table 3) did not significantly change over the same period ($P < 0.2182$).

Table 2. Assessment of the capstone course outcome entitled, “Create technical solutions to complex, open-ended environmental engineering design problems.” The data reflect student performance before and after implementation of 3D printing. Assessment values are based on a Likert scale of one to five, with five representing the maximum positive score.

| | Before 3D Printing (2010-2012) | After 3D Printing (2013-2015) |
|-----------------------------|---|--|
| Overall Assessment Score | 4.14 | 4.24 |
| | 4.22 | 4.03 |
| | 4.22 | 4.24 |
| Average | 4.19 | 4.17 |
| Standard Deviation | 0.04 | 0.12 |

Table 3. Assessment of the capstone course final project grades. The data reflect student performance before and after implementation of 3D printing. Assessment values are based on a Likert scale of one to five, with five representing the maximum positive score.

| | Before 3D Printing (2010-2012) | After 3D Printing (2013-2015) |
|-----------------------------|---|--|
| Overall Assessment Score | 4.20 | 4.39 |
| | 4.38 | 4.18 |
| | 4.05 | 4.36 |
| Average | 4.21 | 4.31 |
| Standard Deviation | 0.17 | 0.11 |

Finally, student response to the following question, “*I feel confident in my ability to create technical solutions to complex, open-ended environmental engineering design problems,*” on the end of course survey (Table 4), did not significantly change over the same six year period ($P < 0.4447$).

Table 4. Assessment of student response to the question, “*I feel confident in my ability to create technical solutions to complex, open-ended environmental engineering design problems.*” The data reflect student performance before and after implementation of 3D printing. Assessment values are based on a Likert scale of one to five, with five representing the maximum positive score.

| | Before 3D Printing (2010-2012) | After 3D Printing (2013-2015) |
|-----------------------------|---|--|
| Overall Assessment Score | 4.80 | 4.30 |
| | 3.67 | 4.20 |
| | 4.20 | 4.25 |
| Average | 4.22 | 4.27 |
| Standard Deviation | 0.57 | 0.08 |

It was hypothesized that the instruments used in Tables 2-4 did not have sufficient precision to capture the influence of 3D printing on student learning. Similarly, Bailey (2015) reported that

implementation of 3D printing did not necessarily result in statistically significant improvements in attainment of student outcomes. On the other hand, assessment data following introduction of 3D printing in a machine design course revealed that 3D printed parts helped the students better understand course topics.² The assessment data used to reach this conclusion (Ref. 2) were based on student comments (indirect assessment) *specific to 3D printing*. Similarly, we revised our end of course survey in 2015 to improve fidelity regarding the effectiveness of 3D printing. Student responses, presented in Table 5, indicate that better than a 2/3 majority valued 3D printing and engineering drawing in the capstone design course. In a similar study, Bailly⁸ reported that informal observations of student performance and engagement suggest that the anticipation of actually fabricating and testing their designs seemed to create stronger student motivation than in prior years. Consequently, it is reasoned that student learning was improved in our program as a result of increased motivation (*cf.* Table 5) through the 3D printing experience. In addition to enhancing the design experience required by ABET Criterion V, introduction of 3D printing also supported attainment of two ABET Student Outcomes. First, Student Outcome (c) “design a system, component, or process to meet desired needs within realistic constraints such as economic, environmental, social, political, ethical, health and safety, manufacturability, and sustainability” was enhanced because 3D printing introduced students to the concept of manufacturability. Second, Student Outcome (k,) “use the techniques, skills, and modern engineering tools necessary for engineering practice” was enhanced because 3D printing is a modern engineering tool.

Table 5. Assessment of 3D printing at the end of the 2015 semester in the capstone design course. Values represent percentages that have been rounded to the nearest whole number, n = 16 students.

| Survey Question | Strongly Agree | Agree | Neutral | Disagree | Strongly Disagree |
|---|----------------|-------|---------|----------|-------------------|
| Printing a 3D model for Projects Day enabled my group to improve their final design | 31 | 38 | 25 | 6 | 0 |
| Printing a 3D model for Projects Day enabled me to better visualize my group's design | 44 | 38 | 13 | 6 | 0 |
| Printing a 3D model for Projects Day helped to enhance my interest in the design | 38 | 38 | 13 | 13 | 0 |
| Learning SolidWorks was worth the effort and enabled my group to produce a better final design. | 56 | 31 | 6 | 6 | 0 |

Conclusion

The inclusion of 3D printing to enhance the design process, communication, and prototype development is an exciting opportunity. The addition of 3D printing for selected projects in our environmental engineering capstone design course has improved students' experiences. 3D printing has also been an effective tool for communicating designs in our independent study courses. In both cases, the instructor had to plan for long project build times that were printed during the same week near the end of the semester. Large environmental engineering designs have been scaled down to create not-to-scale, visual aids that were resistant to breakage when handled. Although SolidWorks is a powerful tool for design of small-scale environmental engineering designs, other software packages may be better suited for large environmental engineering treatment works.

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Appendix: Method for scaling engineering drawings for 3D printing

Following these instructions will allow you to create handheld visual aids of large scale environmental engineering treatment works (e.g. sedimentation basin) and other large engineering designs on our 3D printer. Keep in mind that the 3D printout can only serve as a visual aid because dimensions that are changed will no longer be proportional to the original design. These scaling instructions are necessary to ensure that the product will not come apart, due to failure of plastic components that are too thin. In some cases, use of this procedure will result in no changes to your original dimensions, which will allow you to create a scaled model of your design. This procedure will not correct design flaws that result in printing problems. Thus, the SolidWorks and CatalystEX program must also be used to validate your design before printing.

1. Determine the minimum dimension (d_{\min}) that can be printed. This dimension is a function of the strength of the material that is used for printing (e.g. type of plastic). In our case, d_{\min} is 0.1”.
2. Convert this dimension to the dimensions used in the engineering drawing to be printed (e.g. ft or m).
3. Identify the largest dimension in your design and designate as the maximum dimension (d_m).
4. Identify the largest dimension that can be printed by the 3D printer and designate as the maximum build space dimension (d_{mbs}). (This could, instead, be a maximum dimension that is less than the maximum build space dimension.) In our case, d_{mbs} is 12”.
5. Convert d_{mbs} to the dimensions used in the engineering drawing to be printed (e.g. ft or m).
6. Compute the scale factor (s) as follows:

$$s = \frac{d_m}{d_{mbs}}$$

7. Identify the dimensions that will have to be increased before the drawing is scaled down for printing by calculating the limiting dimension (d_{lim}) as follows:

$$d_{lim} = d_{\min} \times s$$

8. Save your drawing as a new file with the name “3D print” attached to the end of the name.
9. In the new file, scale up (d_{new}) any initial dimensions ($d_{initial}$, in the original file) using one of the two following approaches.

a. In cases where minimum changes are desired, scale up where $d_{\text{initial}} < d_{\text{lim}}$ as follows:

$$d_{\text{new}} = d_{\text{lim}}$$

b. In cases where minimal changes in proportionality are desired, scale up *all* dimensions in the build as follows:

$$d_{\text{new}} = d_{\text{initial}} + d_{\text{lim}}$$