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**STUDYING THE IMPACT OF INCORPORATING AN ADDITIVE MANUFACTURING
BASED DESIGN EXERCISE IN A LARGE, FIRST YEAR TECHNICAL DRAWING AND
CAD COURSE**

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ABSTRACT

Additive Manufacturing (AM) is a revolutionary technology in the manufacturing sector, although it has yet to become a cornerstone of formal engineering education. This paper discusses the procedure, result, and impact of incorporating physical prototyping, design iteration, and Design for Additive Manufacturing (DfAM) in a first-year, first-semester technical drawing and CAD course. In the course, students design balloon powered model car assemblies and are expected to learn core concepts of engineering design, such as modeling, assemblies, and tolerancing. The course consists of 473 students that each design up to two unique model cars. These model cars are fabricated using AM from these CAD designs and returned to students for assembly. Surveys are given to students to empirically validate the usefulness of incorporating AM in the course, with regards to motivating students and improving their ability to accurately translate imagined designs from CAD to physical products. The results show improvement in student intrinsic motivation concerning CAD processes. Student design abilities are also assessed: when student designs do not function as intended, it corresponds with a greater mismatch in how they imagine their CAD design in comparison to its final physical assembly. The mismatch on average decreases for students who design a second model car, which suggests an improvement in design skills. As a whole, our findings demonstrate the feasibility and benefits of including AM in a first-year course, particularly with respect to improving student motivation and their development of key CAD-related skills. Such motivation and skill development is particularly important early in an engineer's career as it can impact their potential to learn and design over the course of their budding career.

INTRODUCTION

Additive manufacturing (AM) is a technology with over thirty years of development that is currently becoming a mainstream manufacturing process poised for large societal impact [1]. The expected societal impact will occur because AM technologies offer unique processes not offered by traditional routes of manufacturing. For instance, AM technology has potential for achieving true mass customization of products designed by users, promoting improved health with customized biomedical products, reducing environmental impact through sustainable manufacturing processes, and simplifying supply chain management to reduce fabrication time and cost. There is a large government and industrial interest in developing AM technologies, with the United States' federal government committing more than \$500 million to promote their wide-spread proliferation [2]. However, contemporary engineering education has not caught up to the fast-paced advancement of AM technologies in recent years [3]. Current university curriculums are possibly ill-suited for preparing engineering students to effectively leverage the technology, which may result in knowledge gaps in the engineering workforce for utilizing AM effectively [4]. In order to investigate new ways of integrating AM in university curriculums, we have developed a first year technical drawing and CAD course at the Swiss Federal Institute of Technology (ETH Zurich) that enables students to design, model, fabricate, and assemble multiple additively manufactured parts early in their education. In this paper, methods are reported for developing and organizing the course content. Additionally, the impact of the course is measured empirically with inventory data collected from students to determine how the course affects first year students with regards to their motivation and development of CAD-related design skills.

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The developed course is unique at ETH because limited coverage of AM exists for first year students [5]. The course is additionally unique globally as ten AM machines are utilized to print designs for over 450 students. Current trends in engineering design education suggest that small educational modules that focus on specific design concepts are highly effective throughout all years of a student's learning [6]. The usage of AM for student projects is particularly interesting in the setting of a semester long course because it enables students to participate in a complete design process including CAD modeling, physical prototyping, design iteration, and AM fabrication. The ability to create a design in CAD and have it fabricated as intended is a vital skill for designers to develop [7], and evidence suggests that undergoing iterations with technical drawing can improve this skill [8]. With these considerations in mind, it is essential to set up the course in a way that enables students to iterate on designs that foster the advancement of these skills.

In developing an appropriate exercise, it is important to maintain a low production cost such that all students can participate in the design exercise [9]. The use of an individualized exercise can also improve student motivation, as it engages each student in the design process directly. Increases in motivation are highly correlated with increased learning for students, and can have large benefits early in a student's education that carry through their entire academic career [10]. In order to promote student motivation and learning, we developed a model car (Figure 1) design exercise [11] due to the model car's low cost and capacity to engage students in aspects of the design process that are essential for CAD and AM, such as designing the car's form for a predefined function.



Figure 1 Sample car design and products to enhance design-based learning

Model cars are particularly relevant in education because they can enhance a student's visual thinking [12], and may consist of multiple modular parts such that students can focus on designing certain aspects of the car while others are predefined, thus ensuring the exercise remains challenging, yet simple enough to promote optimal student learning. The model car utilized in the design exercise (Figure 1) consists of an additively manufactured assembly that house a balloon for propulsion. Throughout this design exercise, students receive well-defined car modeling tasks incrementally, some of which provide students with design customization opportunities. By allowing students to customize aspects of their car, they may be

better able to absorb course content and develop design skills [13]. In this paper, the methods for successfully incorporating the educational approach for including iterative modeling and design exercise are detailed, in addition to empirical results describing the course's impact on student motivation and learning. These findings are essential for motivating the use of design-based exercises early in the engineering curriculum, and readying today's engineering students to effectively utilize AM technologies.

BACKGROUND

The literature reviewed includes the current state-of-art for AM technologies to determine their relevance for the classroom setting, past studies in education for engineering, considerations for improving student motivation, and how student design skills related to CAD processes may be improved.

AM Technologies

AM is a layer-based fabrication process originally developed for rapid prototyping. The expiration of key patents resulted in increasing acceptance of this technology for fabricating complete products [14] [15]. Mass customization is an emerging application, particularly with respect to sharing and printing through web-based platforms. This exercise leverages the process's unique ability to maintain a constant per volume cost independent of the geometric variations in the products. Three major AM technologies are Fused Deposition Modeling (FDM), Stereolithography, and Selective Laser Sintering, with new processes emerging regularly. In comparison with the other technologies, FDM is most suitable for mass production of functional products both in terms of cost and speed [16]. FDM technologies function by unwinding a plastic filament from a coil, and feeding it to an extrusion nozzle. The filament is heated past its glass transition temperature and the material is then deposited.

The Stratasys uPrint SE plus FDM machine is particularly well-suited for classroom settings due to its relative low cost and with a build platform size of $203 \times 203 \times 152$ mm; ten uPrint machines are utilized to print student parts in this study (Figure 2). The model material is ABSPlus plastic. To support overhanging geometries, a brittle, dissolvable material is used. This type of printer is situated between low cost desktop 3D printers and industrial models in terms of cost, need-for-maintenance, robustness, print quality, and print speed. The uPrints are capable of fabricating realistic prototypes and functional plastic parts, thereby they are uniquely suited for batch producing a series of unique parts.

Design for Additive Manufacturing (DfAM) is a recent area of research branching from Design for Manufacturability. DfAM focuses on the manufacturing difficulties pertaining to AM in particular, and attempts to understand, model, and leverage AM capabilities while minimizing cost in all stages of fabrication. According to DfAM principles, designers should consider low volume fabrication, frequent physical prototyping, and intelligent partitioning of an overall assembly in order to leverage the unique capabilities of AM effectively [17].



Figure 2 Student Workshop: 10 Stratasys uPrint SE plus (FDM) Machines

Design and AM in education

In current engineering education, upper year students typically have a selection of numerous courses on matured production manufacturing technologies such as injection molding and die casting. In contrast, few courses on AM exist, especially when considering first year students. Courses that do exist largely use AM as a prototype fabrication alternative to more costly methods with longer turn-around time [18]. Formal design education is also scarce in first year engineering curriculums. It is normally taught in the US through practice in the form of a final year project-based course [18, 28, 29], and it is sometimes the only opportunity where students are given sufficient time and resources to experience the complete design process from conception to prototyping. For example, Bøhn [18] describes a selective-enrollment senior year pilot project that incorporates AM. He stresses the importance of physical prototyping while observing a lack of prototyping in both industry and in engineering curriculums. It was noted that physical prototyping is usually done sparingly and routinely replaced with virtual prototyping [18] due to the time necessary to bring a product to a stage justified for conventional machining and the cost associated with such methods.

With the proliferation of AM, it becomes possible to fabricate prototypes on site and with a significantly lower cost. As a result, the up-front cost and time required to prototype a design is reduced, and this enables its integration in a curriculum [18, 20, 22]. Bøhn suggested extending a similar program to first-year students, though states that the logistics and resources may be a barrier. We intend to outline a method in part to overcome such a barrier.

Past studies in teaching design to first year students have revealed that the choice of exercise in the course is crucial [19]. The exercise must remain reasonable in scope, and if possible a jury judging process can aid in maintaining student interest and sharpening their presentation skills. The inclusion of design skills beyond presentation skills early in a student's curriculum have been investigated in the past, and project-based learning approaches have been particularly successful in promoting learning of design skills [19, 30, 31]. Additively manufactured crystallographic models have been used effectively in science education to improve student comprehension and retention with positive results [20], which suggests that inclusion of fabricated artifacts in a course can convey information beyond models and virtual spaces. These considerations have motivated our current study to include a model car design exercise that is additively

manufactured, to both improve student motivation and aid in their development of CAD-related design skills.

Measurements for student motivation

Motivation is widely studied in psychology, and with respect to motivations in education there are two broad types: intrinsic and extrinsic [21]. Extrinsic motivation refers to sources such as motivating students to complete course work through their grades and deadlines. Intrinsic motivation on the other hand refers to a student's drive to complete tasks through enjoyment of the task itself or a desire to do well on the task. Intrinsic motivation is linked to deep learning of subject matter and is typically considered beneficial for students in achieving success. These types of motivations are typically measured through the use of psychological inventories, and often consist of questions answered by subjects on Likert scales.

Correlational studies have been conducted for student motivation in senior year design projects [22], and suggest that external goals, such as monetary incentives, do not influence student motivation as much as their desire to do well based on intrinsic motivation. However, another study for engineering motivation found that most students operate on extrinsic bases [10]. These findings suggest that the typical engineering curriculum can support both intrinsic and extrinsic types of motivation, although intrinsic motivation is more desirable for learning outcomes. Therefore, our exercise and course presents a unique opportunity to determine whether such additions to the first year curriculum can support an increase in student intrinsic motivation.

Design Skills for virtual to physical design

An important aspect of the DfAM process is the translation of virtual CAD designs to physically printed products. However, past studies have demonstrated accurate translation of information from virtual environments to physical spaces is challenging [23], and can affect how a person perceives experiences with a design [24]. The understanding of virtual environments has been linked to spatial abilities [25], which are improvable over time in engineering contexts through engaging in drawing activities [8]. Abilities specific in forming a better understanding of how virtual reality translates to the real-world have been demonstrated in the medical context through training with virtual interfaces [26]. These considerations suggest that the inclusion of the AM exercises in the first year CAD course can improve student spatial abilities in general through their exposure to drawing processes, and that offering the ability for students to iterate on their designs could possibly result in measurable improvement.

FIRST YEAR TECHNICAL DRAWING AND CAD COURSE WITH AM

The design exercise portion of the first-year, twelve-week long technical drawing and CAD course is implemented with requirements to include a design component, while also incorporating DfAM as a key element throughout. Methods for

effectively printing the large number of model cars required for the course are also developed.

Course Outline

The exercise is shaped around the 12-week duration allotted for the course and the requirement to incorporate an AM component in the curriculum. The general structure of the course starts with technical drawing for three weeks, followed by nine weeks of CAD and modeling. One hour of lecture and three hours of exercises are offered to students each week, with each lecture focusing on a different topic with related exercises (Table 1). The course includes 473 first-year mechanical engineering students in their first semester at ETH Zurich for the Fall 2014 semester. Lectures in the course are developed with the assumption that students' pre-existing knowledge about technical drawing, CAD, and AM are minimal.

Table 1 Course layout, focusing on design exercise related tasks

wk #	Lecture topic	Exercises		Fabrication & Distribution (by staff)
		Type	Design	
1	Intro. & Sketching	TD		
2	Views & Projections	TD		Printing of the standard parts (axles*, chasses, backs)
3	Dimensioning	TD		
4	CAD Introduction	CAD		
5	Modeling Operations	CAD	Chassis	* The axle is not a part of the modeling exercise
6	CAD Features (FBD)	CAD	Wheels	
7	Parametric Design	CAD	Back	Wheels printing
8	Freeform Modeling	CAD	Body #1	Dist. Std. parts & wheels
9	CAD Assembly	CAD	Assembly	Body #1 printing
10	Tolerances	CAD	Body #2	Body #1 distribution
11	Simulation, PDM	CAD		Body #2 printing
12	Review	CAD	Competition	Body #2 distribution

The course begins with technical drawing from weeks one to three and in these exercises students learn to read and produce valid drawings. This knowledge forms a basis for the design skills taught in the model car design. Week four focuses on introducing students to relevant CAD background and fundamentals before introducing the design of the model car in week five when the exercise begins with modeling the chassis. In the week six lecture, AM is introduced with focuses on FDM and DfAM.

From week five to ten, six lecture topics of the model car design exercise is given. Each is complimented by basic modeling exercises where students are asked to model a part described by a technical drawing. The exercise is setup to have students develop incremental aspects of their model car, rather than the entire car at once. The part modeled each week also correlates with the CAD principles taught in the week's lecture. Aspects of the car example are used, where possible, to illustrate fundamentals in the lecture. The students are required to deliver one completed part each week for the first four weeks (weeks five to eight), spend week nine assembling the previously modeled parts, week ten revising the design based on a physical prototype, and the last week (week twelve) testing the final fabricated design.

Step-by-step instructions along with technical drawings are provided to guide students through modeling and assembly of the parts in weeks five, seven and nine respectively. This allows the students to practice their skills in interpreting technical drawings from weeks one to three. By applying the operations taught in the step-by-step instructions and the basic modeling exercises in weeks six, eight and ten, the students work independently on designing and modeling their customized design.

Each of the car parts, including the body revision (week ten), are fabricated with AM. Each part is due for submission one week after the exercise, and is allotted one week of turn-around time for fabrication. The printed parts are distributed in the exercise of the following week.

Model Car

The balloon powered model car exercise is developed because it represents a realistic example of a design assembly that is familiar to students, yet facilitates student creative processes. It also enables students to consider both functional and aesthetic requirements when designing. The model car functions via a balloon fixed with a cylindrical mount at the back of the car for propulsion. The car (Figure 3) is described in detail in the following paragraphs and attention is paid specifically to the DfAM aspects.

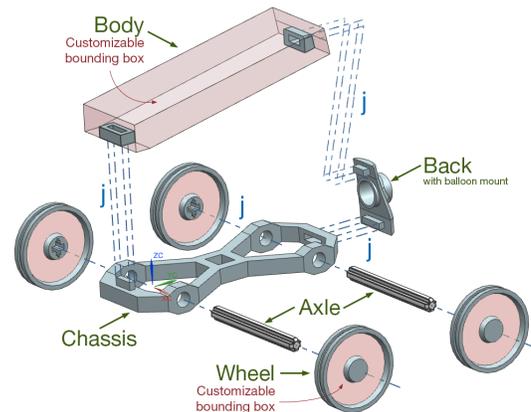


Figure 3 Assembly volume decomposition with customizable parts indicated

The car has a bounding box of $90 \times 48 \times 38$ mm, and a volume of $11,000 \text{ mm}^3$, excluding the customizable parts. To conform to the weekly schedule and education goals, and to reduce material consumption and printing time, the car is decomposed into nine individual parts including one chassis, one back, two axles, four wheels, and one body. The chassis (84×36 mm) and back (25.6×18 mm) maintain the desired outer contour of the car from the side when assembled together. All parts are designed to connect with press fits to eliminate separate connectors.

Physical prototyping and design iteration is incorporated into the design of the wheels and the body, whereas the rest are standard parts intended as CAD modeling tasks. For each customizable part (indicated in Figure 3), a CAD template is provided to the students at the beginning with standardized components already modeled. For the wheel ($\varnothing 30$ mm), the rim

and the hub including the press-fit joint are given. For the body customization task, a bounding box (Figure 3) along with the two press-fit joints are given and students are instructed to limit their design to the bounding box and 5000 mm³ in volume.

In week ten, the first fabricated body is distributed to the students along with balloons so that each student can assemble a complete car with the wheels, chassis, axles, and backs they received on week eight. After informal racing and visual inspection of the physical assembly in week ten, students have the option to design a second body with either incremental changes or a radically new design. Note that this second iteration is not graded. In the last week, the cars are raced to determine which car is capable of travelling the longest distance from each of the five exercise sessions. Further, the students nominate the best design from their session for later online voting by all students to then vote and determine the top three most aesthetic designs that are then awarded.

Logistics for Manufacturing Model Cars

In order to meet the demands of manufacturing hundreds of model cars, a series of logistic and design decisions are considered to optimize the fabrication process to minimize material use and conform to the time constraints set out above. While when using AM integrated components may be fabricated in one-piece without incurring additional cost [17], this exercise is made feasible in terms of fabrication time through volume decomposition shown above. For fabrication, the resulting parts are distinguished as either standard (e.g. chassis, back, axle) or customized (e.g. wheels and body), allowing the standard parts to be printed en masse and in advance, without loading individual model files, thereby saving considerable time.

The chassis is designed to minimize material usage while providing sufficient stiffness. A figure eight shape is chosen for the chasses so that they are staggered on the printing plate during fabrication. Cut-outs are added to further reduce material, and so that the back (with the balloon mount) is printable in the cut-out interior. The parts are placed flat on the printing plate, and the cut-outs and the cylindrical mount ($\varnothing 9.0$ mm) are oriented perpendicular to the printing plate to reduce support material consumption. Simple press fit connections (j shown in Figure 3) are used to hold the parts together so that no additional connectors are needed.

To ensure that the customized parts print as intended, the DfAM constraints specific to the uPrint SE plus proposed by Chen, et al. [11] are adopted and provided to the students prior to each customization exercise. The constraints tested are minimum part dimension, minimum spacing, tolerances, and overhang angles. In particular, a tolerance of 0.1mm is found to result in a tight press fit if the connections are parallel or perpendicular to the printing layers. Additional consideration is given to ensuring that the overhang angles are greater than 45° for as many overhanging geometries as possible. These considerations eliminate most of the in-model support material. The remaining support material in the raft can be manually

separated, while those in the recess of the press fit connections are dissolvable with a chemical bath.

As the standard parts (i.e. chasses, backs and axles) are given back to the students with the wheel in week eight for the first attempt at physical assembly, the standard parts are fabricated prior to week seven in order to prevent bottlenecks. With the above optimization, nine chassis-back pairs or 71 axles may fit on one print plate (Figure 4) and are printed in less than eight hours. The printing is done by student assistants working two shifts per day. For parts that are not designed by students, 460 chasses-back pairs, and 920 axles are fabricated. For student designed parts, 413 customized wheels (week six), 421 body iteration #1 (week eight), and 216 body iteration #2 (week eight) are submitted and fabricated for the 473 students in the course based on the designs they submitted for manufacturing. Since students only need to pass 10 out of 12 exercises, students may choose to not take part in some exercises involving the car.

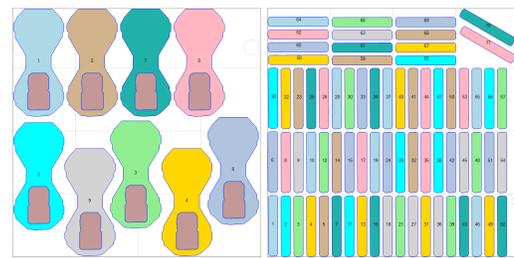
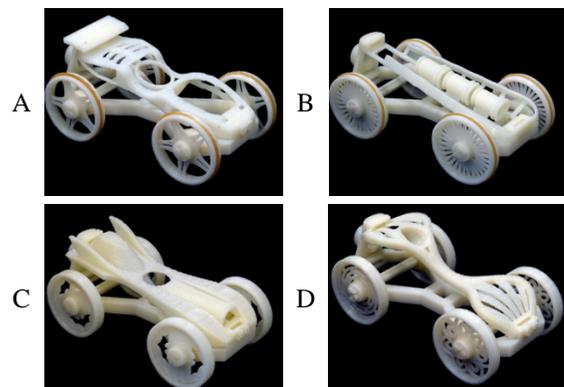
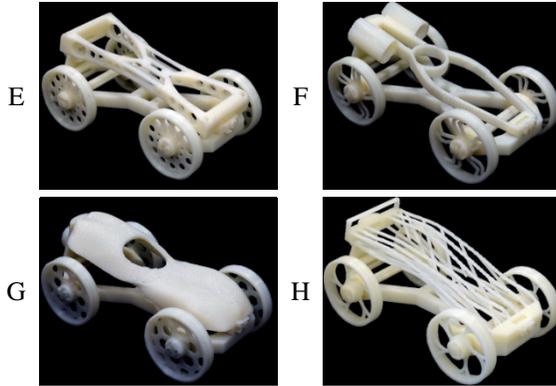


Figure 4 Chassis (Left) and axle packing (Right) on the print plate showing the staggering chassis layout with back integrated, and the layout of the axles

From the fabrication process, all wheels are printed successfully with one exception where the members are too thin and detached. Some first iteration bodies printed as the model file intended, but do not function properly because the students omitted the connections or angled them wrongly. These errors are eliminated in the second iteration. Eight sample model cars designed and assembled by the students are illustrated in Table 2.

Table 2 Selected fabricated assemblies including a portion of winners of the aesthetics challenge (A to F) and the race challenge (A, G, H)





The resulting model cars presented in Table 2 demonstrate the diversity of designs that students are able to create in this exercise. The resulting cars are judged by two criteria, namely maximum distance covered (i.e. the race), and design aesthetics. Designs A to F are six of the 32 winners of the design aesthetics challenge. The widely varying aesthetics across designs and attention to detail suggest that students in the course are engaged in the process, and are motivated to put effort into the design of unique model cars. Design A, G and H are the winners of the race challenge. Overall, this exercise resulted in over six hundred unique car designs when considering the total number of cars fabricated in the course.

EMPIRICAL STUDY ON COURSE EFFECTIVENESS

An empirical study is conducted to assess the effectiveness of the 3D printing portion of the course for influencing student motivation, their perception of key concepts in engineering, and the effect 3D printing has on improving student capabilities for reasoning across virtual to physical design spaces. Data is collected by providing surveys to students at two periods during the course: before their first part is printed and at the end of the course.

Research Questions

Two key research questions are investigated through empirical studies. These questions are based on expectations for how including the model car design exercise may impact student educational outcomes. First, it is predicted that student motivation will increase through participating in the exercise, because effective pedagogical interventions can promote intrinsic motivation in students [10]. Increasing intrinsic motivation is particularly important in comparison to extrinsic motivation, because intrinsically motivated students develop deep approaches to learning and often prefer intellectual rigor over surface approaches.

The second research question investigates whether students are capable of creating CAD models that when printed, match their design intention. This is an important design skill to develop for AM applications, and is linked to student perception of virtual space and its relation to the real world [23]. It is expected that students who produce higher quality designs will also have a better sense of the correlation between

their virtual design and the corresponding product, and that student ability will improve through design iterations [26].

Empirical Study Methods

To answer these two research questions, and assess the pre- and post-effects of student motivation in relation to having their cars printed, two surveys are distributed to students via an online learning platform. The surveys are anonymous and voluntary and are administered during exercise sessions. While students are encouraged to complete the surveys, they are also notified that they have no bearing on their course grade.

The first survey is taken at the beginning of the exercise sessions in week six, prior to distributing the fabricated parts (i.e. pre-exposure). The second survey is distributed in week twelve after the second body is given back (i.e. post-exposure). The purpose of taking these surveys at these times is to have a pre-exposure measurement of students before they interact with any fabricated parts, and a post-exposure measurement after both cars are distributed to determine the effect of including the model-car fabrication process in the course.

The surveys both begin with the same ten questions all rated on a 5-level Likert scale. The first three questions measure students' enjoyment of AM, technical drawing, and CAD. For instance the CAD question is phrased "I enjoy using CAD modeling to design" and then students rate whether they strongly disagree, disagree, have no opinion, agree, or strongly agree. The second set of three questions are phrased to measure a student's perceived value of AM, technical drawing, and CAD, with questions included such as "Learning CAD modeling could help me design better products". The final four questions investigate how important students rate design concepts of iteration, using prototyping to understand scales, considering tolerances, and whether it is important to consider DfAM constraints when designing. The question for rating their importance of DfAM constraints, for instance, is "Understanding of DfAM guidelines affects the final quality of a printed product." Overall, these questions are proposed to measure students' intrinsic motivation (a combination of their enjoyment and perceived value for a task [21]) and their ranking in relative importance of key design concepts. It is noted that all questions are phrased with positive wording, which may result in a positive bias [27]. Further, the number of questions is limited to ten as not to over-tax the students.

The second survey has an additional five questions concerning students perception of their fully assembled cars, which is indicative of the students' success in fabricating the design they envisioned. All students are asked to answer yes/no/not-applicable for whether their first design functions as intended, and whether their second design functions as intended. The not-applicable answer is provided because the second iteration is optional, and because students need only to complete ten out of twelve exercises overall. The third and fourth questions, also on a 5-level Likert scale, ask students whether the physical products of their first and second design iteration are different from their imagined design in CAD. The fifth and final question asks students whether their second

design is better than their first and students are given a choice of yes/no/not-applicable. All survey questions are translated to German by a fluent German speaker to accommodate first year students who are mostly native German speakers; only the translated version are presented to students in the surveys.

Empirical Study Results

Empirical study results are sub-divided into two sections corresponding to the two research questions posed concerning student motivation and design skills. 309 students completed the first survey and 169 students completed the second survey out of the 473 total students in the course. For the second survey, it is found that some students provided answers that are not logically consistent, such as reporting ‘not applicable’ for whether their second design functions as intended, and then answering ‘yes’ for whether their second design performed better than their first. These logically inconsistent responses are removed from the pool of responses when analyzing the final set of five questions. The students who answered ‘not-applicable’ for both designs working as intended are removed as well. This leads to a total of 139 student responses for the final set of five questions.

Student Motivation

The results from the first ten survey questions pre- and post-exposure are reported in Table 3, with measurements provided for the mean and the standard deviation of each survey question. Results are calculated by averaging the Likert scale values reported on the pre- and post-survey for each question individually, while the standard deviation is indicative of the distribution of scores for each response. These questions are asked to address the first research question of whether inclusion of AM in the course altered student motivation. Higher values in the table indicate more positive responses for each concept (e.g. for the enjoyment of an activity questions, a score of 1 means a student did not enjoy the particular activity, while a score of 5 means they enjoy it highly).

Table 3 Results of question set 1 - motivation and design concept mean score and standard deviation for each group.

Focus of the Question	Mean Score of Responses (std. dev.)	
	Pre-exposure	Post-exposure
Enjoyment of Activity		
1) 3D printing (AM)	4.52 (s = 0.62)	4.49 (s = 0.66)
2) Technical Drawing	3.69 (s = 0.98)	3.53 (s = 1.01)
3) CAD	3.86 (s = 0.91)	4.05 (s = 0.73)
Value of Activity		
4) 3D printing (AM)	4.25 (s = 0.77)	4.34 (s = 0.72)
5) Technical Drawing	3.77 (s = 0.88)	3.74 (s = 0.89)
6) CAD	4.06 (s = 0.79)	4.20 (s = 0.70)
Importance of Design Concept		
7) Iterating with physical products	3.96 (s = 0.74)	4.00 (s = 0.74)
8) Prototyping to understand scales	4.28 (s = 0.68)	4.33 (s = 0.70)
9) Manufacturing tolerances	4.31 (s = 0.68)	4.30 (s = 0.74)
10) Understanding DfAM guidelines	3.72 (s = 0.83)	3.76 (s = 0.87)

All statistics are conducted with T-tests and the p values are reported to show statistical significance; p values below 0.05 are generally accepted as indications of statistical significance. When pre- and post-exposure responses are compared, only one result shows significant differences. The CAD enjoyment increase significantly for the post-exposure group ($p < 0.014$), although the students’ placed value on CAD activities also tends towards significance for an increase in the post-exposure group ($p < 0.054$). As students have already conducted CAD activities before the first survey (weeks four to seven), this significant increase in enjoyment occurs in students during the time they experience their virtual design become a physical product.

Although there are no strong differences in pre- and post-exposure results for majority of questions, differences are observed in the relative magnitude for how students enjoy and/or value each activity. Because of the similarities in pre- and post-exposure results, only post-exposure p values are reported for these specific differences. The results suggest that students place greater enjoyment than value in 3D printing ($p < 0.007$), greater value than enjoyment for technical drawing ($p < 0.003$), and greater value than enjoyment for CAD ($p < 0.018$), although the effect size for each is relatively small (Table 2). These results provide a basis for whether student intrinsic motivation for engaging in a particular topic increases because they like the topic, or because they think the topic is important.

When considering intrinsic motivation as the sum of a student’s enjoyment and perceived value of an activity [21], and plotting the results for pre- and post-exposure (Figure 5), the results suggest a significant increase for intrinsic motivation for CAD. Additionally, student intrinsic motivations differ for each primary activity of 3D printing, technical drawing, and CAD. For instance, students are more intrinsically motivated for 3D printing in comparison to technical drawing ($p < 0.001$) and CAD ($p < 0.001$), and are more intrinsically motivated for CAD in comparison to technical drawing ($p < 0.001$). Although students place technical drawing as their least intrinsically motivated activity, they still on average reported a positive Likert scale value for the subject as a whole (above 2.5 on the Likert scale), which indicates they still report positive intrinsic motivation for the task, just not to the same extent as 3D printing or CAD.

For the four survey questions that measure the importance students place on each design concept the course is aimed to teach, pre- and post-exposure results did not vary significantly, but the importance students place on each concept did have significant differences (Table 3). Students consider both prototyping to understand scales and consideration of manufacturing tolerances more important than either iterating with products ($p < 0.001$ for both) or understanding DfAM guidelines ($p < 0.001$ for both). Students also report a greater importance on the concept of iterating with products than understanding DfAM constraints ($p < 0.002$). There is no significant difference between their value for considering prototyping to understand scales and consideration of

manufacturing tolerances. These p -value results are only reported for the post-exposure group due to the similarities in pre- and post-exposure trends. All concepts had positive measures from the student population (above 2.5 on the Likert scale), which suggests that students recognize the importance of each design concept, even as some concepts are rated higher than others.

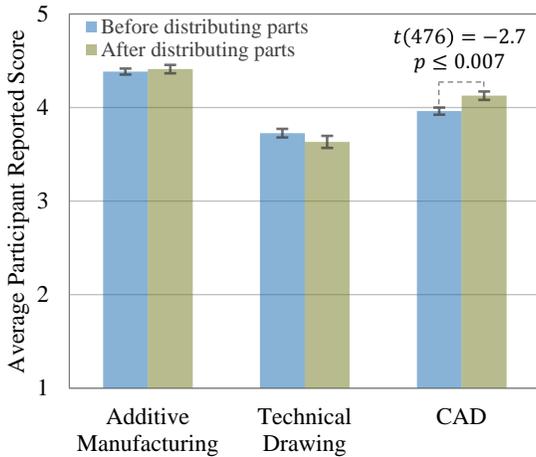


Figure 5 Comparison of average scores for intrinsic motivation for AM, Technical Drawing, and CAD pre- and post-exposure. Scores above 2.5 are considered positive, and below 2.5 indicate a negative response.

Student Design Skills

The final five questions of the survey are only provided post-exposure, and aimed to address the research question concerning the performance of students for translating their intended designs from CAD into final products. Participant results are categorized based on whether students report their designs as functioning as intended or not, and whether they completed one or two designs. This categorization leads to six different groups of students as indicated in Table 4 based on their yes/no/not-applicable choices provided in the survey. These six groups are referred to throughout the paper as the Yes-Yes, Yes-No, No-Yes, No-No, Yes-NA, and No-NA groups based on their reported answer for whether their first or second design function as intended. For example, the No-Yes group refers to participants that report their first design as not functioning as intended, but their second design functioning as intended, while the No-NA group reports that the participant generated one design in total that did not function as intended. If students answered NA-Yes, or NA-No, they are included in the Yes-NA and No-NA groups respectively, meaning these groups reflect students that completed one design throughout the entire span of the course. The number of students in each group is reported in addition to the groups' average Likert measurement for the final three questions of the survey (Table 4). Standard errors of the mean are reported in Table 4 to provide a basis for the accuracy of each measurement. In the table, lower average scores are desirable for questions concerning how different a design is than imagined, while

higher average scores indicate improvement when referring to the second design being better than the first.

Table 4 Post 3D printing questionnaire results for students based on their success in designing functional model cars.

The design functions as intended		# responses	Mean score and standard error of the responses		
1 st design	2 nd design		1 st design was different than imagined	2 nd design was different than imagined	2 nd design was better than 1 st
Students who designed two model cars					
Yes	Yes	39	2.56 ± 0.23	1.97 ± 0.17	3.21 ± 0.22
Yes	No	4	2.50 ± 0.65	3.75 ± 0.25	2.00 ± 0.41
No	Yes	34	3.21 ± 0.21	2.21 ± 0.17	4.09 ± 0.14
No	No	5	3.60 ± 0.68	3.40 ± 0.68	3.60 ± 0.51
Students who designed one model car					
Yes	–	45	2.62 ± 0.16	–	–
No	–	12	3.67 ± 0.31	–	–

The table shows that the majority of students (91.4%) completed at least one functional design. Most students who completed two designs report improvement on their second design (59 of 82), which is found by counting the number of students who report a score of 4 or 5 for that particular question and completed a second design. These results also suggest that students are intrinsically motivated to produce a second design even though it is not required for their grade. Additionally, students generally are more satisfied with their second design as indicated by positive Likert group values of the final question for the Yes-Yes group, and the No-Yes group which made up the majority of students that completed two designs.

To determine whether students who report their design as functional have greater ability to accurately create their CAD model to reflect their printed product, all designs are grouped based on whether the students report them as functioning as intended or not, regardless of their iteration (1st or 2nd). Figure 6 shows the influence of design functionality (functional or not) on the resemblance between the CAD design and the printed product. In Figure 6, a lower value reported indicates that the student's fabricated design corresponded to their imagined design during the CAD process more closely.

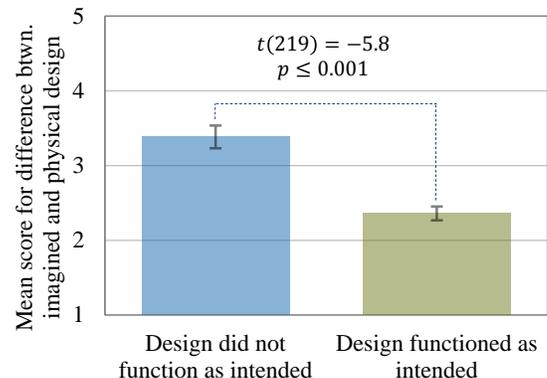


Figure 6 Average user score for how well their imagined design matched the printed one plotted against whether a design functions as intended or not

The results show that when a student's physical design functions as intended, they also report that it matches significantly better to what they imagined when modeling the design virtually in CAD. Significant improvement from the first to the second iteration is observed for both the Yes-Yes ($p < 0.004$) and No-Yes groups ($p < 0.001$) when answering the question of whether the virtual designs matched the physical products. This suggests that through iteration, students improved on how well they are able to convert their imagined design to a physical product.

To determine whether a better match between the imagined design and physical product corresponded to a better design, the difference between a student's first and second reported values for how well their imagined design corresponded to their physical product is determined. A correlation is then conducted between this difference and the student reported values on the statement "my second design is better than my first". This correlation results in a Pearson Correlation of $r = 0.215$ ($p < 0.026$), which supports the idea that students whose imagined designs corresponded better with the physical products also produced designs that they consider better. Study results also suggest the design exercise promoted the growth of student skills in properly fabricating their imagined design as a large portion of students showed improvement in this ability on their second design (46%), in comparison to those that reported a worse second design (11%).

DISCUSSION

The considerations of implementing such an exercise involving AM are first discussed, and then the implications of the empirical study results.

Implementation of the Design Exercise

The particular fabrication process influences the implementation of the design exercise to a large extent. The fabrication success relies on decomposing the complete model car into parts, and incorporating printed connections on these parts for direct assembly. This methodology is in contrast with the AM principles of reducing the number of parts in assemblies and avoiding tolerance issues [17]. The decomposed parts are printed one part at a time in batch, and assembled by students. Also in contrast with the saying that "complexity is free", a series of design constraints such as minimum dimensions, spacing, and angles are provided *a priori* to the students to ensure that resulting models can be fabricated as-is without inspection and/or modification by technicians.

The logical sequence of information and lectures guiding students through the design exercise also influences their growth throughout the study. Technical drawing (weeks one to three) is taught first to form a basis of knowledge in reading and creating mechanical drawings. Then CAD and a CAD tool are introduced (week four), allowing students to model what they read from the drawings. Following that, the design exercise starts with modeling primarily 2D parts such as the chassis (week five). A similar set of operations are intended to be used creatively by students during the following week (week

six) in designing the wheels, another 2D structure. The first 3D exercise focuses on modeling the car back and a step-by-step instruction set is given (week seven). Following that, students design the first car body with the skills they learned from the car back (week eight). The assembly exercise is placed in week nine so that students learn virtual assembly first in the CAD tool, and so that printing of the first car body can take place. In week ten when all the physical parts are received, students assemble and test their complete physical product. From the test results, they have the opportunity to improve their car body design (week ten).

Impact of the exercise

Results from the survey suggest that while students recognize the value in technical drawing, CAD and AM, they value technical drawing to a lesser extent than CAD or AM. When considering measurements in student motivation for these subjects, only the mean value of the student-reported intrinsic motivation for CAD improves after being exposed to physical products. This result may have emerged from students recognizing that their physical design is different than what they imagined in the virtual space; consequently, they realized that CAD is a more important skill than they had previously thought. Conversely, students do not conduct the same level of iteration in technical drawing during the course, which may explain why student motivation/enjoyment of the topic do not change significantly. Student motivation regarding AM may not have improved significantly because students are removed from the direct experience of actual fabrication that was completed by teaching assistants.

CAD-related design skills are also measured from student surveys. The perceived functionality and success of the physical product correlates significantly with a student's reported similarity between it and its virtual counterpart. Conversely, when a student's design did not work as intended, students tend to report a large difference in how they perceive the CAD and printed design. In both the Yes-Yes and No-Yes groups, the gap between imagined and printed design narrows, suggesting that physical prototyping and iteration are important in improving design ability, which means the course have a positive impact in not only affecting students' motivations, but also improving key design skills.

CONCLUSION

This paper demonstrates impacts of including a design project that is fabricated with AM as a part of a technical drawing and CAD course for first-year, first-term mechanical engineering students. The project engages 473 students in design customization, physical prototyping using AM, and iteration for a balloon powered car design. The course results in the fabrication of over 400 unique car designs with fused deposition modeling. The exercise is designed to teach students the concepts of design, CAD modeling, tolerances, and DfAM.

Data concerning student motivation and design skills in the course are collected using surveys before and after their cars were fabricated. The primary results for the motivation portion

of the survey suggest that student intrinsic motivation for CAD increases, but no significant change is observed with respect to technical drawing or DfAM.

The second portion of the survey measures student design skills and find that students who indicated that their product functions as intended also tend to indicate that their fabricated product matches more closely to the intended design configured with CAD. When a second design iteration is conducted, students tend to report that the virtual-physical resemblance further improved. These results suggest that with physical prototyping through AM, students are able to more effectively transfer their imagined designs from the virtual CAD space to the physical design space.

Overall, these findings demonstrate the effectiveness of integrating design and AM in a first year engineering curriculum. These results are quite timely as there is increasing accessibility to AM technologies, and suggest that engineering schools could benefit from incorporating similar design exercises in their curriculum to raise student motivation and design skills. The introduction and impact of such exercises for first year students can be monumental for their continued interest and success as engineers, and this paper presents findings to foster such growth early in engineers' careers.

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REFERENCES

- [1] S. H. Huang, P. Liu, A. Mokusdar and L. Hou, "Additive manufacturing and its societal impact: a literature review," *The International Journal of Advanced Manufacturing Technology*, vol. 67, no. 5-8, pp. 1191-1203, 2013.
- [2] President's Council of Advisors on Science and Technology, "Report To The President On Ensuring American Leadership In Advanced Manufacturing," Washington D.C., 2011.
- [3] C. B. Williams and C. C. Seepersad, "Design for Additive Manufacturing Curriculum: A Problem-and Project-Based Approach.," 2012.
- [4] T. W. Simpson, C. B. Williams and M. Hripko, "Educational Needs and Opportunities in Additive Manufacturing: Summary and Recommendations from a NSF Workshop," Solid Freeform Fabrication Symposium, Austin, 2014.
- [5] Department of Mechanical and Process Engineering, ETH Zurich, "Bachelor-Studienführer," Zurich, 2010.
- [6] C. Telenko, B. Camburn, K. Hölttä-Otto, K. Wood and K. Otto, "Designettes: New approaches to multidisciplinary engineering design education," Buffalo, 2014.
- [7] L. Sass, "Materializing design the implications of rapid prototyping in digital design," *Design Studies*, vol. 27, pp. 325-355, 2006.
- [8] S. Olkun, "Making connections improving spatial abilities with engineering drawing activities," *International Journal of Mathematics Teaching and Learning*, 2003.
- [9] J. McLurkin, J. Rykowski, M. John, Q. Kaseman and A. J. Lynch, "Using multi-robot systems for engineering education," *IEEE Transactions on Education*, vol. 56, no. 1, pp. 24-33, 2013.
- [10] N. Savage, R. Birch and E. Noussi, "Motivation of engineering students in higher education," *Engineering Education*, vol. 6, no. 2, pp. 39-46, 2011.
- [11] T. Chen, K. Shea and F. Stöckli, "Design for Customization in Small Series Production using Additive Manufacture: Case-Study of a Balloon-Powered Car.," 2015.
- [12] E. Taborda, L. Kisselburgh, T. Reid and K. Ramani, "Enhancing visual thinking in a toy design course using freehand sketching," Chicago, 2012.
- [13] C. B. Williams and F. Mistree, "Empowering Students to Learn How to Learn: Mass Customization of a Graduate Engineering Design Course," *The International Journal of Engineering Education*, vol. 22, no. 6, pp. 1269-1280, 2006.
- [14] T. J. Horn and O. L. A. Harrysson, "Overview of current additive manufacturing technologies and selected applications," *Science Progress*, vol. 95, no. 3, pp. 255-282, 2012.
- [15] J. Manyika, M. Chui, J. Bughin, R. Dobbs, P. Bisson and A. Marrs, "Disruptive technologies: Advances that will transform life, business, and the global economy," McKinsey Global Institute, 2013.
- [16] Stratasys Inc., "A New Mindset in Product Ddesign: 3d Printing Can Help Bring Better Products To Market Faster," 2014.
- [17] I. Gibson, D. Rosen and B. Stucker, "Design for Additive Manufacturing," in *Additive Manufacturing Technologies*, LLC, Springer Science+Business Media, 2010, pp. 283-316.
- [18] J. Helge Böhn, "Integrating rapid prototyping into the engineering curriculum - a case study," *Rapid Prototyping Journal*, vol. 3, no. 1, pp. 32-37, 1997.
- [19] C. L. Dym, "Teaching Design to Freshmen Style and Content," *American Society for Engineering Education*, vol. 83, no. 4, pp. 303-310, 1994.
- [20] P. Moeck, J. Stone-Sundberg, T. J. Snyder and W. Kaminsky, "Enlivening 300 level general education classes on nanoscience and nanotechnology with 3D printed crystallographic models," *Journal of Materials Education*, pp. 1-20, 2014.
- [21] R. Ryan and E. Deci, "Intrinsic and extrinsic motivations: Classic definitions and new directions," *Contemporary educational psychology*, vol. 25, no. 1, pp. 54-67, 2000.
- [22] A. Bessette and V. Okafor, "Correlating Student Motivation to Course Performance in Capstone Design," Buffalo, 2014.
- [23] E. Arthur, P. Hancock and S. Chrysler, "The perception of spatial layout in real and virtual worlds," *Ergonomics*, vol. 40, no. 1, pp. 69-77, 2010.
- [24] N. Tovaes, P. Boatwright and J. Cagan, "Experiential conjoint analysis an experiencebased method for eliciting capturing an dmodeling consumer preference," *Journal of Mechanical Design*, vol. 136, pp. 101404-1 - 12, 2014.
- [25] A. Rafi, K. Anuar, A. Samad, M. Hayati and M. Mahadzir, "Improving spatial ability using a web-based virtual environment (WbVE)," *Automation in Construction*, vol. 14, pp. 707-715, 2005.
- [26] N. E. Seymour, "VR to OR A Review of the evidence that virtual reality simulation improves operating room performance," *World Journal of Surgery*, vol. 32, pp. 182-188, 2008.
- [27] R. K. Garg, "The influence of positive and negative wording and issue involvement on responses to Likert scales in marketing research," *Journal of the Market Research Society*, vol. 38, no. 3, pp. 235-246, 1996.
- [28] M. A. Omar, "Design and Implementation of a Capstone Course to Satisfy the Industry Needs of Virtual Product Development and ABET Engineering Criteria," *Education Research International*, pp. 1-18, 2014.
- [29] MIT, "Engineering Design and Rapid Prototyping," 2007. [Online]. Available: <http://ocw.mit.edu/courses/aeronautics-and-astronautics/16-810-engineering-design-and-rapid-prototyping-january-iap-2007/index.htm>. [Accessed 21 12 2014].
- [30] P. Little and M. P. Cardenas, "Use of studio methods in the Introductory Design Curriculum - Copy," *Journal of Engineering Education*, vol. 90, no. 3, pp. 309-318, 2001.
- [31] J. M. Case and G. Light, "Emerging methodologies in engineering education research," *Journal of Engineering Education*, vol. 100, no. 1, pp. 186-210, 2011.