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A Framework to Analyse Digital Fabrication Projects: The Role of Design Creativity

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Abstract: In this study, we formulate a framework to evaluate open-ended projects related to digital fabrication. The framework consists of two dimensions, i.e. human intellect and technology. Human intellect is judged by three sub-dimensions – creativity, computational thinking, and skills. In order to study the technology dimension, the four sub-dimensions include process, outcome, development stage, and reproducibility. To test the proposed framework, a case study was applied on digital fabrication projects done in Fab Academy 2019. Final projects of students are selected to implement the framework since final projects exemplify most of the skills learned by a student of the digital fabrication course. In addition, the proposed framework is also assessed in the light of existing literature done to evaluate learning in similar types of projects. The results establish the relationship among different sub parameters of human intellect and technology, and present the open-ended project evaluation results.

Keywords: *digital fabrication, project-based learning, fab lab, design creativity, evaluation*

1. Introduction

The purpose of this research is to evaluate open-ended digital fabrication projects and help with the learning process in this field. We tried to formulate a framework which can be applied on a wide range of open-ended projects related to digital fabrication, based on dimensions used in the specific literature. Innovation and digitization are the two constants in the rapidly advancing world of manufacturing. The revolutionary concept of digital fabrication, also known as computer-controlled manufacturing, empowers humans to transform ideas into final products. Turning digital data into reality is a fully automated process, shepherding coding into physical world by using different Computer Aided Design (CAD) and Computer Aided Manufacturing (CAM) software tools. There are numerous digital fabrication techniques and processes, which enables even an amateur to create, design, prepare, and fabricate using digital fabrication tools.

Despite the promising benefits of ‘making’ technologies and ‘maker events’, in encouraging students to create innovative projects, different critical factors raise concern over the effectiveness of digital fabrication projects. Bringing in powerful ideas, encouraging imagination and creating meaningful projects, designing sustainable tools, designs and products, studying models on the market, mainstreaming into commercialized products, the lack of empirical research to explore the reality of digital fabrication, and constructionist learning are some of the critical factors in investigating the manufactured projects.

2. Background

The increasing number of Fab Labs worldwide has drawn more attention from researchers in recent years towards discussing the effective learning of students. They have come up with various models, comprising of multiple parameters and criteria that help assess Fab Lab projects during different phases of a project's life cycle. According to many scholars and innovators (Dewey, 1902; Blikstein and Worsley, 2016), the prime objective of education should be centred on real-world problems and experiential learning (Blikstein, 2013). There are multiple models proposed, for example, by engineers, educationists, or hobbyists, analysing multiple dimensions of open-ended projects, such as originality, relatedness, constructive learning, confidence, ease of documenting, exploring ideas, learning skills, and creating useful products. One such study was done by the German federal research project 'FAB101', which consisted of 4 groups of researchers that took into consideration the local state of the art, methodologies, and infrastructure of German Fab Labs, performing some experimental and empirical work and comparing it with the undergoing developments in international labs, in the same sectors of personal digital fabrication (Stickel, 2018). Another research was planned in Fab Lab Madrid by Covadonga Lorenzo (CEU University Madrid), who focused on inculcating the Seymour Papert's concepts of 'learning by doing' and 'learning while having fun'. The test group in this study were high school STEM students who were encouraged to perform practical work by applying the theoretical concepts they acquired, using digital fabrication as a learning tool. In the two-week program, they were granted access to the Fab Lab and all the required tools. The results were satisfying, and students were able to gain some knowledge and experience in teamwork, communication, or design thinking (Lorenzo, 2017). This study further proved the significance of constructionism – 'learning by constructing knowledge through the act of making something shareable' (Martinez and Stager, 2013).

Creativity is a crucial standard in measuring the usefulness of a student's projects in digital fabrication. It varies from student to student and depends on multiple factors, such as background knowledge, department of study, hardware and software skills, teamwork, confidence, and ability. In this regard, a qualitative analysis done by Georgiev et al. (2018) helps in examining the novelty of ideas generated during the digital fabrication course and allowed open access to different resources. Also, this research focused on demonstrating the importance of digital fabrication processes required to develop an end product. During the 9 weeks of the digital fabrication course, students' creativity and idea generation were evaluated on the basis of their final prototypes and documentation. This qualitative analysis found that student's previous knowledge influenced their creativity and collaboration within a team. Moreover, students tend to actualize their goals after initial trials and consider modifying or compromising the goals of their project. A case study on a digital fabrication workshop determined the significance of useful projects in relation to the perspective of participants. The qualitative analysis was made using different tools, namely questionnaires and individual interviews, evaluating presentations, documentation (pictures and explanatory texts), and final prototypes (Georgiev et al., 2019). The results showed that participants' backgrounds and their motivation to undertake a particular project was a key determining factor for attaching realization to the project. Another important study surveyed different digital fabrication processes and techniques, such as designing or electronics production, based on knowledge, confidence, enthusiasm, and participants' involvement (Sánchez Milara et al., 2017). At the end of a two-week training program, the participants demonstrated an increased level of confidence and an enhanced motivation to undertake future projects related to digital fabrication. Usually, training programs and different research methodologies – surveys, questionnaires, interviews, and previous records – are used in evaluating students' learning. Thus, the evaluation of projects further assists trainers, instructors, and maker communities in improving the learning experience of students.

The aim of this study is to formulate evaluation and comparison criteria for the human and technological dimensions of digital fabrication projects. To this endeavour, we use recent Fab Academy projects.

3. Method

Based on the dimensions used by Sánchez Milara et al. (2017), the proposed framework adds more details for quantifying the existing state of the art framework used in literature. This is done by defining the sub-dimensions in each category and their evaluation criteria. The following literature sources in the revised paper describe the existing framework. Sánchez Milara et al. (2017) discussed technological and human dimensions concerning digital fabrication within the Fab lab context. The technological dimension includes the design of 3D/2D parts, prototyping using electronics, programming, and utilizing tools/machines in the Fab lab. The human dimension includes experience/knowledge, confidence, motivation, and fun. These two general dimensions are concerned with the experiential aspect of students and participants in digital fabrication activities. In the current study, we focus on the educational aspect and the placement of experiences besides outcomes in the overall picture of fabrication and making phenomena. For data collection and implementation, we conducted a case study on a sample consisting of 18 Fab Academy 2019 projects (see Appendix) to propose a set of specific dimensions in terms of human intellect and technology. The Fab Academy projects are representative for long-term digital fabrication projects that are essentially open-ended and depend on students' ideas and creativity. Typically, they are also complex in covering various approaches, tools, and skills involved in digital fabrication.

4. Evaluation Criteria for Fab Academy Projects

4.1. Human intellect

The human intellect dimension is used to examine the learning aspect which has a direct impact on students' cognitive learning. It also assesses the use of their abilities for creative design. This dimension is divided into three sub-dimensions, each with its own criteria to evaluate and score. Aspects such as creative ideas and knowledge gained by the student are assessed. Furthermore, the evaluation takes into account the student's background and special professional skills in order to get a clear idea of the student's learning, from a sociological perspective. The criteria to rate each sub-dimension is given in Table 1. Previous studies used similar dimensions for a framework in order to capture creativity in digital fabrication projects, well-defined by Georgiev et al. (2017) and Borges (2017), who explained the importance of computational thinking in these types of projects. They also identified the elements to be evaluated in related projects. In the case of Fab Academy, many skills are taught to make digital fabrication projects. Therefore, in final projects it is required to incorporate most of the skills to ensure maximum learning. However, there are certain cases when students needed or already had a distinct skill, apart from the skills being taught in Fab Academy. Therefore, for evaluation it is interesting to test the skills utilized by a student in a project.

Table 1. Human intellect sub-dimensions with corresponding criteria and evaluation scales

Sub-dimensions	**Criteria**	**Evaluation scale (1-4)**
Creativity of student	Use of creativity techniques Creativity of the working prototype(s) Creativity of the product Number and quality of alternatives explored	1 to 4. Depends upon the level to meet the criteria
Computational Thinking	Elaborates an algorithm Elaborates an execution flow for an equipment assembly or to perform a task Elaborates a scalable solution Elaborates a script with instructions for using the created solution	1 to 4. Depends upon the level to meet the criteria
Skills	Requirement of specialized skills to reproduce the product	1. Very specific digital fabrication skills and/or knowledge required (beyond typical Fab Academy level) 2. Specific digital fabrication skills required (Fab Academy level) 3. Basic digital fabrication skills General technical skills, not related to Fab Academy

4.2. Technology dimension

Another crucial dimension to evaluate open-ended projects is the 'employment of technology in open-ended projects', which is further divided into four sub-dimensions. There is plenty of background work done to assess the use of technology in such projects. In this framework, the technological dimension is thoroughly analysed. The first sub-dimension is the process involved in the project – it usually requires processes such as electronics, embedded programming, additive or subtractive manufacturing, and 2D/3D designing. If a project is fabricated integrating all these processes, it will be marked with the highest score. Similarly, the second sub-dimension is the outcome of the processes performed. If a process is performed imitating the way it was taught, then the outcome will be marked with a low score. If a student performed the process without using the examples given, thus creating unique interfaces, it will be marked with the highest score. The third sub-dimension is represented by the project development stage. If it is complete in all aspects, ready to be used, then the project is in its final stage of development and it will be marked with the highest score. If it is only the prototype for the proof of concept, then it will be scored accordingly, under this category. The fourth and the last sub-dimension is the ability to reproduce the project. If the project is made using standard Fab Lab software and hardware tools, then it can be easily reproduced in another lab, therefore, it will get the highest reproducibility score in this category. Similar dimensions are also used in the available literature. Milara et al. (2017) used the process as a dimension to measure the technical skills of high school students, in their experiment. Similarly, prototyping and its development is discussed and evaluated by Analytis et al. (2012). Mellis (2011) wonderfully defined the stages from prototype to final product of a project in his case study on the digital fabrication of open-source consumer electronic products.

Each activity has certain outcomes; the most common possible outcome in digital fabrication processes are defined in Table 2.

Table 2. Technological sub-dimensions with corresponding criteria and evaluation scales

Sub-dimensions	**Criteria**	**Evaluation scale (1-4)**
Process	Electronics production	1. If any of the processes is used 2. If any two processes are used 3. If any three processes are used 4. All processes are used
	Embedded programming	
	2D/3D designing	
	Manufacturing technique (Additive/Subtractive)	
Outcome	Examples used or customized the code	1. Basics of all outcomes 2. Basics of all items and one at advanced stage 3. Two at basic stage and two at advanced stage 4. All advanced stage. No part taken from examples
	Parametric, non-parametric design, 3D or 2D, press fit designed or not	
	Number and typological variety of machines used (CNC, Laser, Vinyl) etc	
	Inputs and outputs	
Stage of development	Initial stage (Idea)	1. Initial stage 2. Partially completed prototype 3. Completely functional prototype 4. Commercial product
	Unfinished prototype stage	
	Working prototype	
	Product (ready for commercial usage)	
Reproducibility	Unavailability of information (Documentation)	1. If all the statements are true, low reproducibility 2. If more than one is true 3. If only one is true 4. None of them are true
	Requirement for specific components unavailable in FabLab inventory	
	Specific tools/machines	

4.3 Case study results

Figure 1 shows the results of the criteria applied on the first four projects mentioned in the Appendix. Project 1 is a prototype of a system which will maintain the temperature of a mug placed inside it. It was fabricated in Fab lab Bahrain by an engineering student who learned electronics and programming as additional skills. The project employed different skills, such as 3D design and printing, laser cutting, electronics, and programming. However, the use of the large CNC machine is missing from this project. Project 2, labelled as ‘Fab buddy’, is an embedded device assisting the Fab lab instructor in managing lab resources by limiting machine access to authorized people only, and allowing them limited time slots. This project was designed and fabricated by a computer professional in échoFab Fab Lab. It consists of a completely embedded device integrating multiple inputs, outputs, and controls. Although it has an on-screen display, it does not have any computer or mobile interface. Its casing is made by a laser cutter. The CNC machine is not used is this project, either, except for the small CNC which was used to fabricate printed circuit boards (PCBs). Project 3 was made to detect facial emotions. It was fabricated in Fab lab UAE by an undergraduate student with some basic knowledge of electrical engineering. The project used neural network-based algorithms running in MATLAB (external software) to detect facial emotions. A system was designed to detect the face and another to send the data from camera to PC, using Fab Lab resources. This project provided a computer interface and all major skills taught in Fab Academy were applied, including the usage of the CNC machine. Project 4 is a giant breadboard for STEM education design, fabricated by a person with a background in industrial design and education. This is a creative idea implemented with the main skills taught in the Fab lab, such as electronics, 2D and 3D designing and printing. It does not have any kind of mobile or computer interface. Overall, it was considered an efficient utilization of Fab Lab tools to implement a creative idea. Uneven scales can also be used in an evaluation. The reason for subcategories is to quantify the impact of that dimension on the student’s learning curve. If a criterion does not apply, it can be rated zero. As the selected projects are successfully completed by Fab Academy students, 0 is not used in any category.

After applying the proposed framework, Figure 1 shows the rating of the first four projects mentioned in the Appendix. This figure displays the rating of each dimension of a specific project, showing if a particular process is present in the project or not. If the process is present then it is evaluated according to the number of skills related to that process. If all the skills are identified, then the project will be rated ‘4’ for that particular process or sub-dimension. If some skills in a certain dimension are missing, then the project will be rated accordingly. All these conditions are defined in the ‘evaluation scale’ column in tables 1 and 2. The results of the first four projects is displayed in Figure 1 to clearly exemplify the contribution of each sub-dimension. The evaluation results for all project is shown in Figure 2.

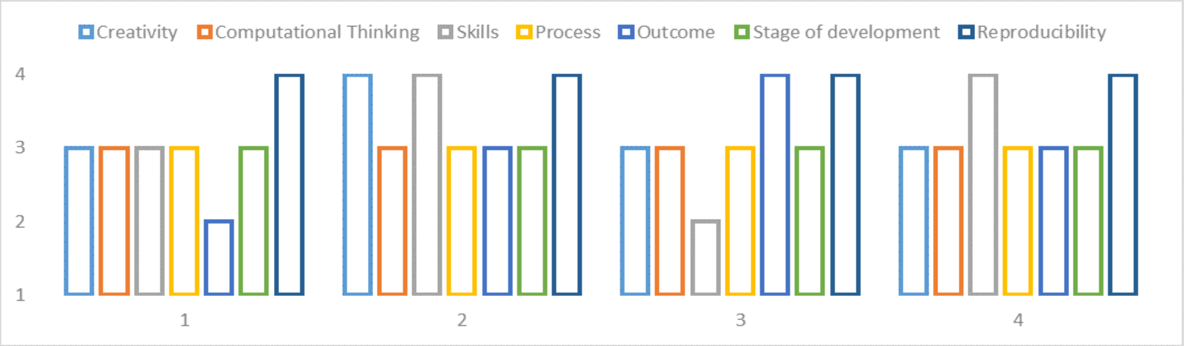

Figure 1. Case study result of four selected projects

Figure 2 displays the overall results of the case study applied on all projects. The X axis indicates the projects mentioned in Appendix, and the other two axes represent the dimensions and the score scale of the proposed framework. The figure shows that all projects received 2 or more points for each dimension due to the fact that all the projects were successfully completed by the Fab Academy 2019 students, and verified by internal and external examiners. This aspect ratifies our framework used to evaluate such open-ended projects.

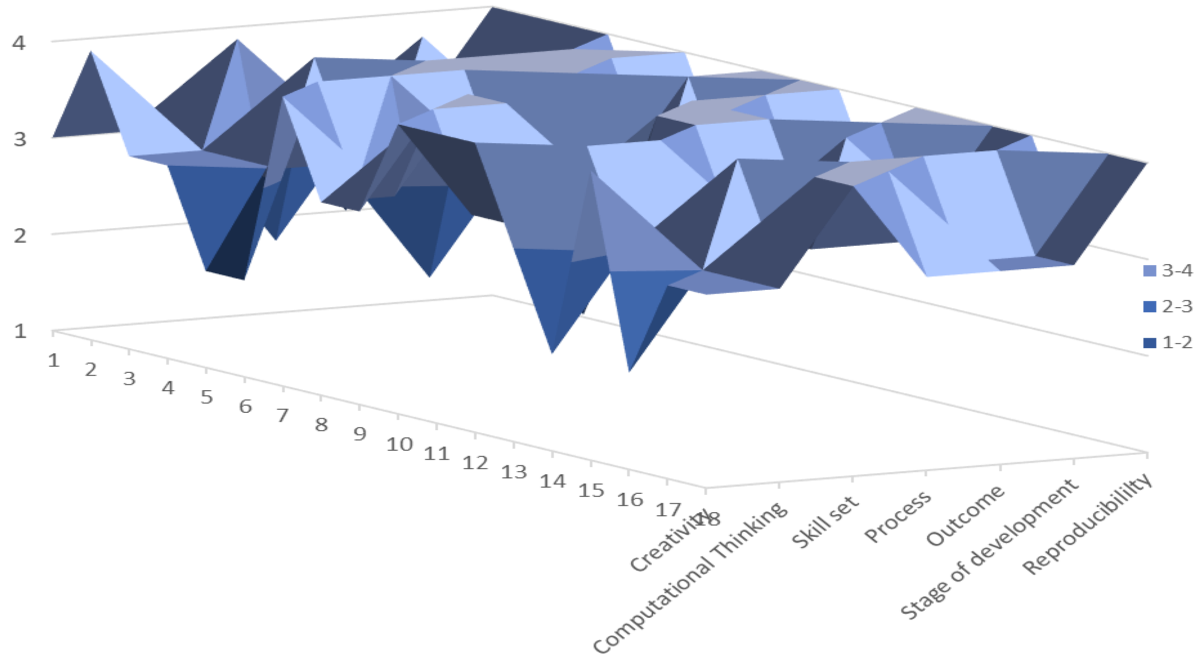

Figure 2. Case study results of all 18 projects

Figure 3 is a pie chart representing the average for each sub-dimension of all projects under consideration. All sub-dimensions weighted equally in the project evaluation, except for the high percentage registered by reproducibility. This is due to the fact that the majority of the students used the standard FabLab tools to implement the prototypes, therefore, the possibility to reproduce the project in any other FabLab in the world is high.

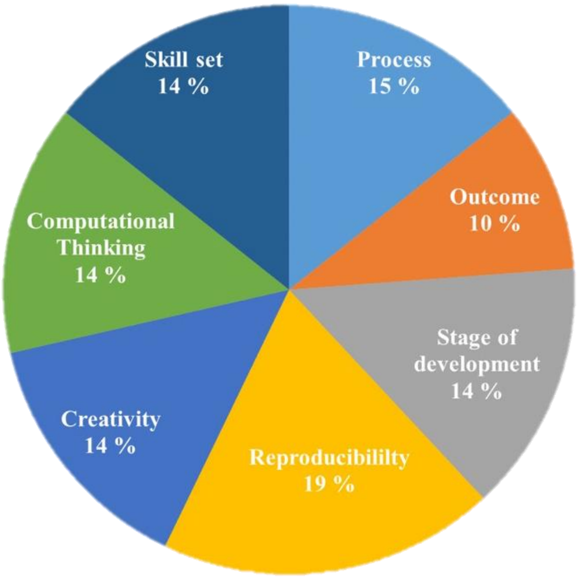

Figure 3. Relation between the sub-dimensions

5. Discussion

One of the motivations for this research was that, in the future, this framework can be used to evaluate students' work/projects using an automatic computer program. Most of the students report their progress by writing up a web-based document/blog, as in the case of Fab Academy and the Principles of Digital

Fabrication course of the University of Oulu. Therefore, through this framework, a computer program would help identify what are the things needing access or evaluation.

What is the role of these criteria in the perspective of design creativity? The proposed evaluation criteria in terms of students' creativity tackles the issue from the viewpoint of design process, in time. Typical design creativity studies focus on a shorter time span or do not account for the genealogy of ideas and prototypes. Recent studies have shown that the genealogy of ideas is essential for successful solutions, and the genealogy of prototypes is essential for effective design thinking (Vestad et al., 2019). Furthermore, the stage of development criterion also tackles the issue of design creativity, as the stage of an idea and its prototyping are related.

The proposed evaluation criteria encompass different sub-dimensions that account for essential characteristics of digital fabrication and maker movement, such as reproducibility and required skill sets. A large number of students are working on digital fabrication projects and learning new skills by doing open-ended projects. Previous studies examined the impact of proposed sub-dimensions (belonging to both technological and human dimensions) in student learning. Building upon those dimensions endorsed by the literature, we tried to develop a framework to evaluate open-ended projects. In this study, for example, we accounted for the creativity of the working prototype(s) and number/quality of the alternatives explored. By doing so, we tried to incorporate holistic views to idea generation and prototyping. As an early exploratory study, limitations can be sought in terms of the scale of the utilized data and the need for further verification of the proposed evaluation criteria. These open issues will be addressed in further work.

6. Conclusion

This research represents an effort to collect information regarding the evaluation of open-ended projects from the literature endorsed through experiments. The study focused on applying a set of criteria to evaluate open-ended projects of digital fabrication. The criteria selected were based on the technology used and the skills learned by students, and they were obtained by dividing each aspect, i.e. human and technology, into different sub-dimensions. A case study was also conducted to apply the proposed framework on recent projects of Fab Academy done by students in 2019. A sample of 18 projects was selected to test the framework. The results of the case study show the learning of students, who have completed their final projects on a scale of 1 to 4 in each sub-dimension of human and technological aspects. The learning curve of a student can be deduced from these numbers, for each specific category. Only final projects of Fab Academy students were selected for testing the proposed criteria which integrate the maximum number of skills learned by the student during the digital fabrication course. As the final project represents the superset of the small projects, the framework and the criteria of each sub-dimension tested can also be applied to examine any weekly/small projects. For future research we suggest a more detailed definition of the evaluation scale, which will be helpful in acquiring more specific data.

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Appendix

List of Fab Academy 2019 Projects selected for case study.

1. http://fabacademy.org/2019/labs/bahrain/students/fatima-jahromi/projects/final-project/
2. http://fabacademy.org/2019/labs/echofab/students/philippe-libioulle/capstone.html
3. http://fabacademy.org/2019/labs/uae/students/salem-almarri/final.html
4. http://fabacademy.org/2019/labs/ulb/students/amy-beaulisch/finalproject.html
5. http://fabacademy.org/2019/labs/irbid/students/tarek-asfour/manoove.html
6. http://fabacademy.org/2019/labs/tecsup/students/silvia-lugo/final.html
7. http://fabacademy.org/2019/labs/ulb/students/gilles-decroly/presentation.mp4
8. http://fabacademy.org/2019/labs/barcelona/students/gustavo-deabreu/projects/__final_project
9. http://fabacademy.org/2019/labs/bahrain/students/zainab-ali/presentation.png
10. http://fabacademy.org/2019/labs/berytech/students/joseph-zoulikian/presentation.png
11. http://fabacademy.org/2019/labs/dassault/students/jose-fuenzalida/presentation.png
12. http://fabacademy.org/2019/labs/lccc/students/brent-richardson/presentation.png
13. http://fabacademy.org/2019/labs/kannai/students/yozi-shimakawa/presentation.png
14. http://fabacademy.org/2019/labs/kannai/students/kota-tomaru/presentation.png
15. http://fabacademy.org/2019/labs/kannai/students/takayuki-sakai/presentation.png
16. http://fabacademy.org/2019/labs/khairpur/students/tariq-ahmed/presentation.png
17. http://fabacademy.org/2019/labs/rwanda/students/ndacyayisaba-raymond/presentation.png
18. http://fabacademy.org/2019/labs/oulu/students/marjo-leinonen/presentation.png