

The Application of Digital Fabrication in Architecture, Case Study: Prototyping a Scale Model

Hendro Trieddiantoro Putro
Architecture

*Faculty of Science and Technology
University Technology of Yogyakarta
Yogyakarta, Indonesia
Hendro.putro@staff.uty.ac.id*

Wiliarto Wirasmoyo
Architecture

*Faculty of Science and Technology
University Technology of Yogyakarta
Yogyakarta, Indonesia
wiliarto.wirasmoyo@staff.uty.ac.id*

Abstract—Technological developments in architecture continued such as parametric design methods with computational optimization process and digital fabrication to make a scale model. Digital fabrication defined as the process of manipulating objects using CNC router machines, 3D printers, and laser cutters through reduction or addition methods. This technology believed in providing convenience advantages in making an architectural scale model, which gives more precise results with a faster manufacturing process.

Furthermore, the understanding above brings consequences for both the students and lecturers of architecture. For the example in the teaching of technical matters such as the optimization of 3D models for fabricating processes, selecting techniques and materials, and also the installation. So studying digital fabrication is a necessity in architecture academics. Both students and lecturers required to improve their understanding and ability to process digital designs into a representation of scale models through fabrication method.

The research purpose is identifying the teaching procedure of digital fabrication in producing architectural scale models. The method is to analyze the questionnaire from the architecture students that join the workshop. This workshop will introduce a digital fabrication with a computational optimization process using Grasshopper. Architecture student will be given a questionnaire at the beginning and end of the workshop. At the end of studies show that digital fabrication provides convenience and challenges for architecture academics.

Keywords: *parametric design, digital fabrication, architectural scale models*

I. BACKGROUND

The history of fabrication technology starts with mass production that introduced and developed by Henry Ford, founder of Ford Motor Company in early of the 19th century [1]. This method worked with producing the replicated model. Therefore, the correlation between quantity, time, and predict the quality accurately, and operational costs are cheaper.

In Architecture, as in Lisa Iwamoto's Digital Fabrications Architectural And Material Techniques that CAD technology replace drawing, digital fabrication brings new understanding and expand the boundaries of architectural form and construction[2],

Moreover, Seely explains that digital fabrication influences the process of architectural design because of its essential role supporting the making of architectural models [3]. Correspondingly with Seely, Dunn explains the reasons why students and the architect profession make models. Representation of creative ideas is vital in design-based disciplines and is very relevant in architecture where we often cannot see the result, namely building that built, until the end of the design process. The initial concept developed through a process that allowed the designer to investigate, revise, and further refine ideas in detail that increased to the point in such a way that the design of the project ready to build. Models can be extraordinarily versatile objects in this process, allowing designers to express thoughts creatively [4].

Digital fabrication, as in the digital age, has filled the gap between conception and production. Creating a direct digital link through "file-to-factory" processes of computer numerically controlled (CNC) fabrication [5].

The use of digital design and digital fabrication for architecture student increasingly becomes an ordinary skill [6].

This digital design and fabrication technology paradigm was explained by Stoutjesdijkas industry 4.0, which aims to make digital fabrication techniques available to everyone. It is a shift from the world of consumers to producers, where everyone can produce energy, information, food, and commodities, based on shared knowledge networks and digital fabrication devices [7].

II. PARAMETRIC DESIGN AND DIGITAL FABRICATION

A. Parametric Design

Wassim Jabi in his book "Parametric Design for Architecture" says that parametric design is a design process based on algorithmic thinking which brings out the details of a parameter, where the parameters together strengthen and clarify the relationship between design goals and how the design will respond to problems [8].

Parametric design is a concept that enables the designer to define relationships between elements or groups of elements, also assign values or expressions to organize and control those definitions [9]. Dunn added that the process

continues until desired results are chosen based on relevant “performative” and aesthetic criteria. For the inexperienced, the parametric-design process is initially very time-consuming. However, it depends on the willingness to learn [10].

B. Digital Fabrication in Architecture

In the early 2000s, from prototyping equipment, such as laser cutters and 3D printers, dramatically dropped in price, and Open Source hardware further popularized these technologies. Digital fabrication technology became better and more accessible, and the intellectual activities enabled by the new technology became more valued and important. Industrial designers could create prototypes in days instead of months [11]

There is a considerable definition of digital fabrication, a process that begins with digital design and ends with output from a fabrication machine. Digital fabrication is an educational and activity paradigm in which multidisciplinary knowledge incorporates 2D design, 3D design, use of tools and machines. Digital fabrication comes from CAD (Computer-aided design) then transferred to CAM (Computer-aided manufacturing) software. The output from CAM ready to fabricated to a specific machine, like a 3D printer or CNC milling machine.

C. Educating Digital Design and Fabrication

The first digital fabrication laboratories in architectural schools came up in the late '90s, and they were a result of the collaboration with mechanical engineering laboratories [12]. Rapid prototyping and CNC routers were the first machines for fabricating models in architecture. In the following years, techniques and strategies have rapid expanding. Mainly there is 3 step for digital fabrication work [13], there are:

- Digital design phase. This first step is creating a virtual model using CAD software. The 3d model exported as triangulated mesh or surfaced.
- The Preparing phase. Step for setting the manufacturing parameters and specific to the fabrication, resulting in a CAM file then send to the machine.
- Fabricate phase. Fabrication tools manufacture parts based on the CAM data, with little or no human assistance or interaction. Assembling the fabricated parts might need to achieve their final properties and look before they are ready to use.

The focus of the fabrication phase [14]:

- Externalise ideas and concepts into mock-ups, prototypes, and products.
- Select analog and digital materials to transform ideas into prototypes and products.
- Work creatively and exploratively to construct with different fabrication technologies.
- Visualize and represent artifacts in various ways while continuously adjusting.

III. RESEARCH METHOD

The research purpose is identifying the teaching procedure of digital fabrication. The method is to analyze the questionnaire from the architecture students that join the workshop. This workshop is open for architecture student at University Technology Of Yogyakarta. It will introduce a digital fabrication process that starts with a parametric design learning then computational optimization process using Grasshopper. Architecture student will be given time to fill in the questionnaire at the beginning and the end of the workshop.

A. Digital Design and Digital Fabrication Workshop



Fig. 1. The Digital Design and Digital Fabrication Workshop

Through the workshop, the student will come to understand the procedures of basic levels of grasshopper as digital design tools and optimization the file for fabrication. The workshop contains the process of digital design, which consists of applying a parametric design, optimization phase, then preparing the fabrication file. In the workshop, Fig. 1., the student learns how to make the 3d model using grasshopper and preparing the fabrication, but not fabricate. The researcher shows the final scale model for explaining the result of the process.

B. Questionnaire

Questionnaires submitted to respondents before and after completing workshops. The questionnaire was filled in by each respondent by their response to the workshop. The results of the questionnaire that had been answered by respondents were analyzed by converting the answer options.

Questionnaire Page 1

- 1 What is your name
.....
- 2 Choose one:
 Male Female
- 3 What year of architecture students are you now?
 1st year
 2nd Year
 3rd Year
 4th Year
 5th Year
 >5th Year
- 4 Do you know digital fabrication?
 yes
 no
- 5 Digital fabrication technique that you know (may choose more than 1)
 Laser cut
 3d print
 cnc milling
 others /
- 6 Have you ever applied digital fabrication for college assignments?
 yes (go to page 2)
 No (go to page 3)

end of questionnaire page 1

Questionnaire Page 2

- 1 assignment you are working on using digital fabrication (may be more than 1)
.....
- 2 The digital fabrication technique that you used for assignments (may be more than 1)
 Laser cut
 3d print
 cnc milling
 others /
- 3 The software that you use to prepare the model for fabrication (may be more than 1)
.....
- 4 what kind of problem did you encounter (May be more than 1)
 3d Model making
 Optimization for fabrication
 Assembling the part
 others /
- 5 Evaluation of your digital fabrication work
Precision / scale Very Dissatisfied
 Dissatisfied
 Neutral
 Satisfied
 Very Satisfied
- Aesthetic Very Dissatisfied
 Dissatisfied
 Neutral
 Satisfied
 Very Satisfied
- Time spend for fabrication Very Dissatisfied
 Dissatisfied
 Neutral
 Satisfied
 Very Satisfied
- Price issue Very Dissatisfied
 Dissatisfied
 Neutral
 Satisfied
 Very Satisfied
- Utility Very Dissatisfied
 Dissatisfied
 Neutral
 Satisfied
 Very Satisfied
- durability Very Dissatisfied
 Dissatisfied
 Neutral
 Satisfied
 Very Satisfied

end of questionnaire page 2

Fig. 2. Questionnaire Page 1 and Page 2

The most positive (very good, very agreeable, and very satisfied) answer choices are converted to 5. While the results of the answer choices are very negative (very bad, very dissatisfied, strongly disagree) converted to 1.

Questionnaire Page 3

- 1 Digital fabrication and parametric design are interrelated
 Very disagree
 disagree
 Neutral
 Agree
 Very Agree
- 2 Digital fabrication and parametric design courses are needed
 Very disagree
 disagree
 Neutral
 Agree
 Very Agree
- 3 I will take part in elective courses on digital design and fabrication
 Very disagree
 disagree
 Neutral
 Agree
 Very Agree
- 4 I will apply digital fabrication to make scale models
 Very disagree
 disagree
 Neutral
 Agree
 Very Agree

end of questionnaire page 3

Fig. 3. Questionnaire Page 3

There is 3 page of the questionnaire, Fig. 2. the 1st-page questionnaire contains six questions. It is questioning about personal data and familiarity with digital fabrication, also did they had applied digital fabrication. At the end of the questionnaire page 1, there is a yes or no question about have they ever applied digital fabrication before the workshop, for them who had any experience with digital fabrication can go to the 2nd-page, while for those who did not have may skip the 2nd-page of the questionnaire and take to 3rd-page of the questionnaire.

The 2nd-page of the questionnaire in Fig. 2. is for them who had an experience with digital fabrication. This page of the questionnaire is questioning the detail of their project of digital fabrication and the problem they encountered, also assessment of digital fabrication product. Fig. 3. the 3rd-page of the questionnaire is questioning about their response to the workshop and their interest in the elective course for digital fabrication.

IV. DISCUSSION AND ANALYSIS

The workshop held on building technology class at University Technology of Yogyakarta. It held in 1 day, two weeks before the student final exam. Their one final exam is to make a scale model for architecture studio presentation. The total participant was 155 students that spread in different years of study. There is three digital design course to be delivered with laser cut and 3d printing as digital fabrication technique. The researcher is instructing digital design using rhinoceros and grasshopper. These tools allow changing the parameters that define the geometry and make immediate modifications of the model during design. The student is new with rhinoceros and grasshopper. They will learn the software and the digital design process through the workshop. Also, the researcher is ready with the final product of digital fabrication for better explaining. The questionnaire is given as the workshop start and collected when the workshop ends.

A. Digital Design and Digital Fabrication Workshop

1) Course 1 - Laser cut - Waffle Structure

The waffle structure is made using an algorithm in grasshopper. Before start making the 3d model, it is must be ensured the scale in rhinoceros. Mainly the process in Fig. 4. is making a section as the 3d model shape then reorient the surface into X-axis and Y-axis. The numbering of the surface for fabrication also done in grasshopper.

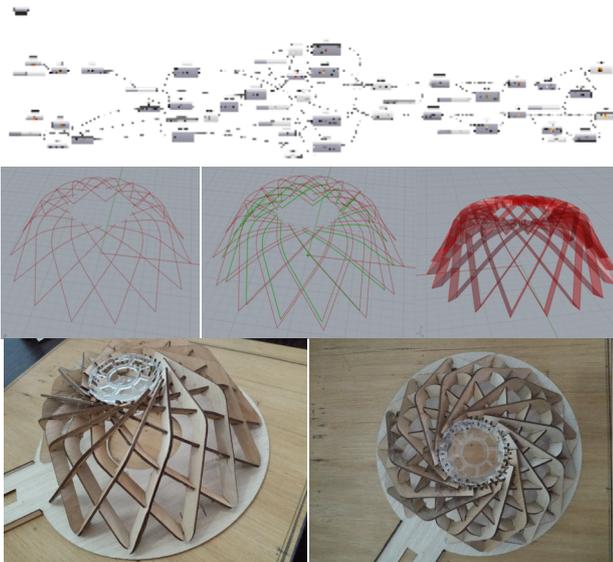


Fig. 4. Process of Making a Waffle Structure

2) Course 2 - Laser Cut - Voronoi Structure

The Voronoi structure is done with the laser-cut process then attaching the edge for assembling the part. The Voronoi structure in Fig. 5. made with an algorithm in grasshopper.

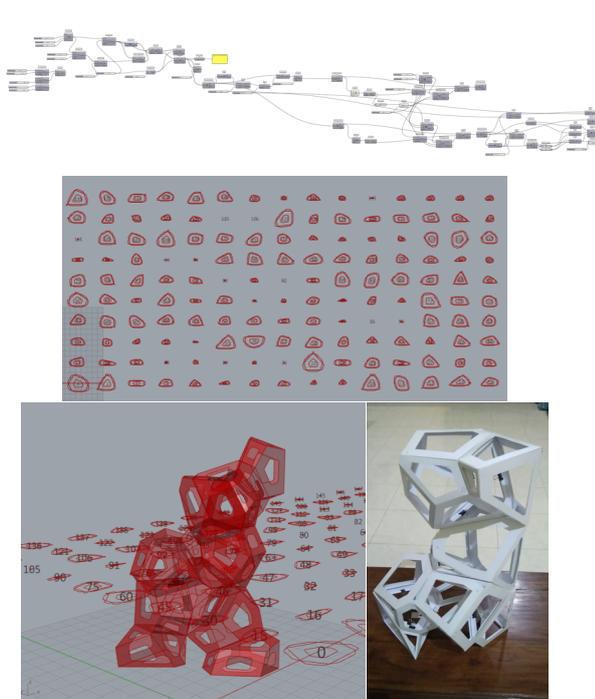


Fig. 5. Process of Making a Voronoi Structure

The optimization process is completed with surface reorienting and numbering. The final step is giving the border edge for the sticky zone and edit the color of line to 2 types, cut and engrave.

3) Course 3 - 3D Print - Voronoi surface

This course will explain the process of 3d printing. It starts with designing using the algorithm in grasshopper, then the optimization process using Cura for fabrication. The student is learning from the fabrication process video. In this video will be given a successful and failed example.

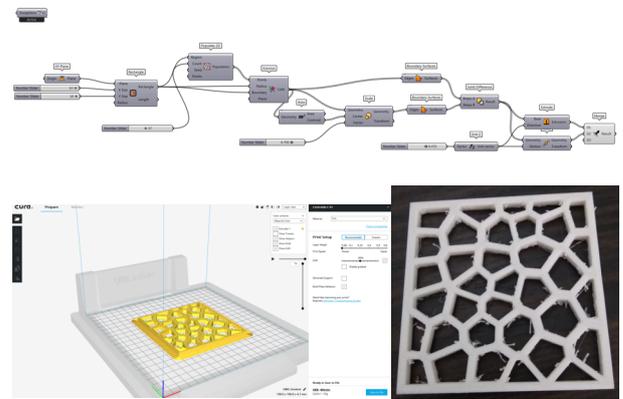


Fig. 6. Process of Making a Voronoi Surface

Fig. 6. is a simple additive layer of Voronoi is made using an algorithm in grasshopper then sent to Cura. Cura software will give the estimation of fabricating duration. The duration of 3d printing is approximately 6 hour.

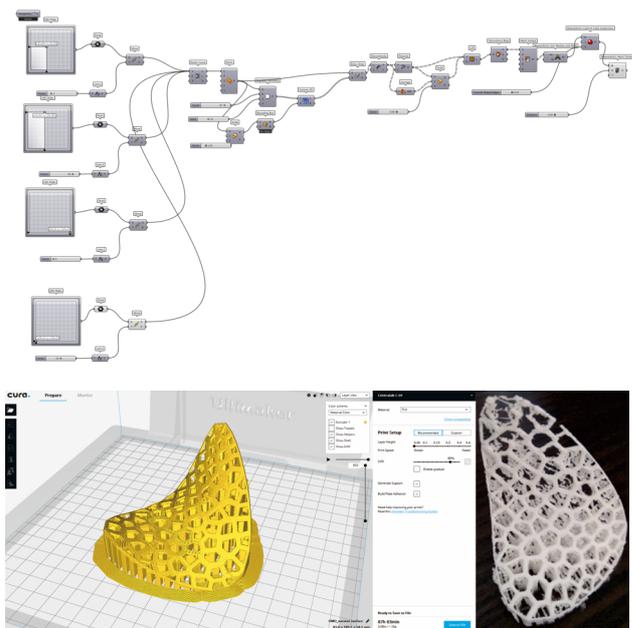


Fig. 7. Process of Making a Voronoi Structure

There is Fig. 7. an example of failed 3d printing product, the researcher clarifies the problem encountered when fabricating to the student at the workshop. The problem appears when fabricating the curved surfaced. The failed part is at the top layer. At least three times of trial and error have been done to achieve the desired results.

There is a question and answer part in the workshop before they fill the last questionnaire. Student curiosity increases as many students asked further about their problems faced when preparing 3d model for fabrication.

Referring to the workshop, the digital design process using parametric design tools such as rhinoceros and grasshopper is the proper way of preparing 3d model to fabrication. The similarity founded in research by Agirbas [15], Stavric [16], Austern [17], that the students gained some experience in creating non-standard forms and modified with parameters, also had the opportunity to learn about the digital fabrication process. Furthermore, this is in good agreement for educating digital fabrication based on Blikstein [11]. He said that a fabrication lab is needed for engineering and invention so that students could safely make, build, and share their creations. It accelerates invention and design cycles, with long term projects and deep collaboration. Just like the quote from Marshall McLuhan, "We become what we behold. We shape our tools and then our tools shape us." [18]. Moreover, Nemorin adds that the deepening of digital fabrication material in a workshop can be more effective if the student is trial and error themselves[19].

B. Questionnaire Analysis

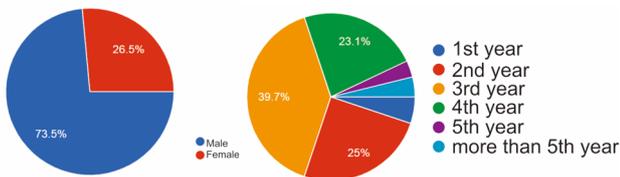


Fig. 8. Participant Background

One hundred fifty-six architecture students join the workshop that spread to various levels of the year. As shown in Fig. 8. that there are 73,5% or 115 male students, and 26,5% or 41 female students. The workshop respondent is dominated by 2nd to 4th-year architecture student. More details on this, 39,7% of the respondent or 62 students are in their 3rd-year of their architecture study. While 25% or 39 of the respondent are in their 2nd year and 23,1% or 36 of the respondent are in their 4th year of study.

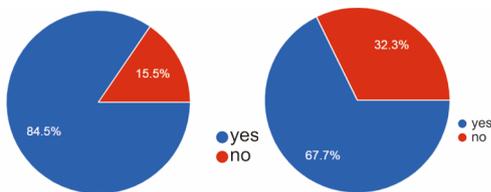


Fig. 9. Student Familiarity (left) and Experience (right) with Digital Fabrication

Fig. 9. shows that there are 84,5% or 132 of respondents that knew about digital fabrication. While 67,7% or 106 students that used digital fabrication for their task. Also, Fig. 10. shows 93 students recorded that knew and had applied digital fabrication and 13 students that had applied digital fabrication even they are not familiar with digital fabrication.

The student that knew and had applied digital fabrication from 3rd year and 4th year dominate the workshop, it is

showed from Fig. 10. the graph of student familiarity with digital fabrication below. Another high number in the graph is about the student that knew but have not applied digital application. It spread to 1st year to 4th year of the student. The graph below shows that digital fabrication used in the 2nd-year to more than 5th-year architecture student.

Fig. 11. shows a comparison of student familiarity to

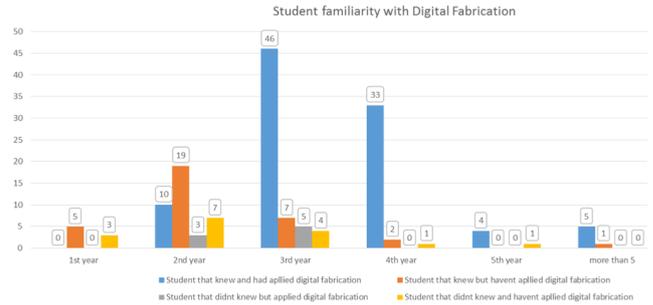


Fig. 10. Student Familiarity with Digital Fabrication

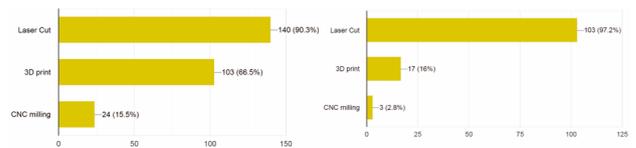


Fig. 11. Student Familiarity (left) and Experience (right) with Digital Fabrication Technique

utilization with digital fabrication technique. Apparently, from 156 students that join the workshop, about 90,3% of them familiar with laser-cut, 66,5% of them familiar with 3d print, and 15,5% of them familiar with CNC milling. While only laser-cut that the most used technique with 97,1% or 103 students using laser cut method, 16,2% or 17 students using 3d print, and only 2,9% or 3 students using CNC milling.

Shown from Fig. 12. above, the student assignment that assisted with digital fabrication is an architecture design studio and building structure. The 3rd-year and 4th-year

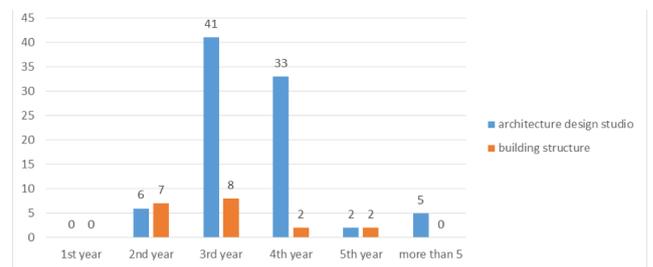


Fig. 12. Student Assignment Assisted with Digital Fabrication

students are the most frequent student year that using digital fabrication. Moreover, the architecture design studio is the most assisted subject with digital fabrication. Also, mainly, there is three software that used to prepare the model for fabrication, such as Sketchup for 3d model making, Autocad, and Corel Draw as shown from Fig. 13. below.

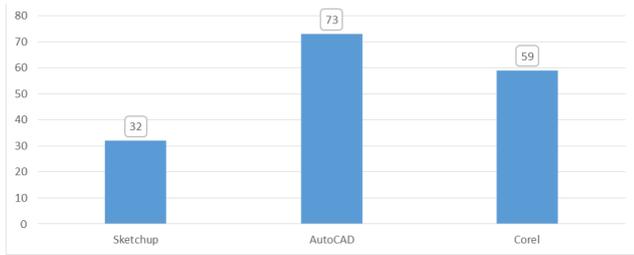


Fig. 13. The Software Used for Digital Fabrication

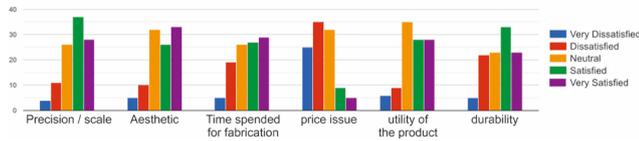


Fig. 14. Student Responses to Their Digital Fabrication Work in Questionnaire Page 2

The Fig. 14. explain about the questionnaire 2nd page, the question that investigates about student responses to their digital fabrication work shows that mainly they are satisfied with their digital fabrication product, such as precision or scale, the aesthetic, time that spends for fabrication, the utility, and the durability. However, it found that they were dissatisfied about the price for fabrication product. The student satisfied with the time spends for fabrication found different from Nemorin [19], because they mostly use laser-cut than 3d print.

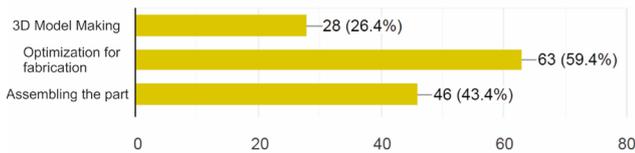


Fig. 15. Problem of Digital Fabrication that Student Encountered

From Fig. 11. of the comparison of student familiarity to utilization with digital fabrication technique brings up that laser-cut technique most often used by the student. There are two most significant problems. The graph above shows that frequently encountered by the student when applying digital fabrication is 59,4% optimization when preparation a file for fabrication and 43,4% for assembling the part. While 26,4% of respondent had a problem in 3d model making phase, these findings are similar with Nemorin that in her research that there is a frustration in 3d model making phase because digital design projects require understanding and precision in science and mathematics, they also require trial and error, and perseverance [19].

Further analysis, file preparation becomes the most severe problem for student because of the face object reorientation process, reorienting the 3d object to the X and Y axis, then become more time consuming when they reorient the face one by 1. While, the problem in the assembling part, student encountered many similar objects and wrong numbering object that's what makes students find it challenging to assemble. The workshop tries to respond to this issue using parametric design tools such as rhinoceros and grasshopper

[20][21]. The workshop contains the process of digital design using grasshoppers such as waffle structure and Voronoi structure [15], also optimization phase and preparing the fabrication file for laser cutting. The assembling part problem as Thorsten explained is natural for learning digital fabrication, especially do not always hinder the student, and keep the momentum [22].

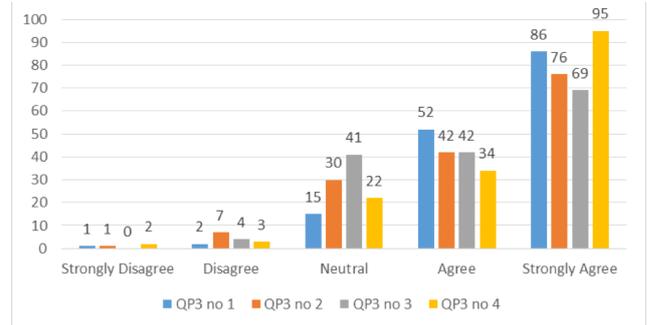


Fig. 16. Student Responses on Questionnaire Page 3

The graph above is the response for the questionnaire page 3 or QP3. There are four questions on this page. It shows that the respondent's trend is on agreeing on the statement in questionnaire page 3. More details from QP3 no 1, about 86 student or 55,1% of all respondent strongly agree that digital fabrication and parametric design are interrelated. Moreover, on QP3 no 2, 76 students or 48,7% of all respondent strongly agree that they need digital fabrication and parametric design course. Survey of QP3 no three shows that 69 students or 44,2% of the student will take part in elective courses on digital design and fabrication. While QP3 no 4 is a statement with the most vote from 95 students or 60,9%, that they strongly agree will apply digital fabrication to make scale models.

The challenge of educating digital fabrication is a term of mass-producing with little effort as Blikstein describes the "Keychain syndrome" using the lab as a fabrication facility, rather than a place for invention. Also, Thorsten describes as digital design plagiarism, the sheer number of possible sources for plagiarism online [22]. The opportunities from learning digital fabrication are it brings a new understanding of the possibilities of design and creation software which for construct designs that would be very difficult to develop using traditional methods. At the workshop, we learn that designers are no longer only users of manufacturing tools, but we were actively involved in adjusting fabrication tools. This condition supports the idea of the designer as tool-maker [11].

V. CONCLUSION

The questionnaire report that student's familiarity with digital fabrication is high, especially the utilization laser-cut technique that prepared using Sketchup as 3d model making, AutoCAD, and Corel, which help the student architectural design studio assignments. Mainly they are satisfied with their digital fabrication product but dissatisfied about the price for fabricating the product.

Moreover, the optimization file and assembling part was mostly the problem for the student that deals with digital

fabrication, despite the 3d model making as well but not significant. The workshop succeeds to introduce digital fabrication process and its correlation with digital design in making of a scale model, which using grasshopper as a parametric design tool. The workshop confirmed that digital design and digital fabrication are interrelated. Digital design is a vital part of the process which brings convenience in the next stage. The student finds digital design using grasshopper such as experimenting with waffle structure, and Voronoi structure is exciting and brings up a comprehension which is indicated by their interest in taking digital fabrication as an elective course.

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