Innovative Approach to Design and Development of a 3D Silicone Printing Machine Using Transdisciplinary Integrated Design Tools

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Abstract:*In this paper, we introduced the integration of well-known TD tools that have been applied in many fields including product development, project management, many engineering disciplines, design of the organization, sustainable development, social issues, environmental issues, and others across many industries including automotive, aerospace, telecom, semiconductor, defense, transportation, energy, health-care, agriculture, and more. The main objective of this paper is to introduce a new transdisciplinary (TD) engineering-based integrated approach to designing and developing a 3D silicone printing machine (SPM). Factors in designing and developing 3D SPM were simplified by considering the main factors affecting the performance of 3D SPM. Results are discussed and the modular 3D silicone printing machine design was presented. Using the Axiomatic Design (AD) tool, components of each module were identified to satisfy the functional requirements of the 3D SPM. Six TD-integrated tools were used to design the 3D SPM in this research. They are Quality Function Deployment (QFD), House of Quality (HOQ), TRIZ, AD, Interpretive Structural Modeling (ISM), and Design Structure Matrix (DSM).*

Keywords:3D printing machine design, silicone printing, integrated transdisciplinary tools, House of Quality; Quality Function Deployment; Interpretive Structural Modeling; Design Structure Matrix; Axiomatic Design; Kano Analysis; KJ Diagram; Critical to Quality.

1 Introduction

3D printing and additive manufacturing (AM) methods, processes, and most advanced applications are rapidly evolving and are innovative advanced technologies that empower the manufacturing of lighter, stronger, safer, and more cost-effective components and products.

3D printing has come a long way in the past 20 years. Additive manufacturing is changing the landscape of complex medical engineering. Advances in medical 3D printing technology have made huge contributions to the fields of healthcare – reducing the duration of surgery and anesthesia exposure, helping in better pre-surgery planning, manufacturing patient-specific custom replicas of bones, tissue, bioprinting, and replacing human organ transplants – the applications are endless. X-rays, CT scans, and handheld ultrasound integrated processes with 3D printing have become game-changers.

Researchers in additive manufacturing have a profound interest in new processes and materials suitable for 3D printing applications [1, 2]. For example, in medical engineering, current heart valve solutions are costly and labor-intensive for fabrication, have relatively short life spans, and include animal-derived tissue (bioprosthetic) or metallic elements that require immunosuppression or anti-thrombogenic drugs, which have significant undesirable side effects. Moreover, the replacement valves presently used are circular that may not fit perfectly into the patient's aorta which is different for each patient [3].

Using CT scans of the patient's heart to recreate the exact shape of the aortic root region and using silicon 3D printing, an artificial custom-made heart valve can be created as a functional implant. In comparison to the existing mechanical heart valves and tissue valves, the above-mentioned method seems to be promising. Silicone is a good candidate for the material to manufacture heart valves because of its similar compliance to the native tissue and known biocompatibility. Although silicone is biocompatible, silicone heart valve parts manufactured will not be used in the human body at this time. Initially, they will serve as a model to mimic the behavior of bioprosthetic valves. Eventually, in the future, 3D-printed silicone heart valves could be adapted for use as implantable synthetic heart valves [3]. Although silicone offers amazing possibilities in healthcare, electronics, and other fields, most 3D printable liquid silicone rubber (LSR) is still in the R&D phase and is not commercially available yet [4].

4D printing technology adds an exciting new dimension by going one step beyond 3D printing to include a fourth dimension–time. The 4D printing process is inspired by the way plants change shape over time in response to environmental stimuli [5]. This new technology requires complex materials, customized designs, and processes to activate the 3D print to its shape transformation when triggered by a specific stimulus, such as external energy input, water, or other changing conditions. While 4D printing is in the beginning stages and still in the R&D phase, it's already being used in medical, aviation, and other industries. The emergence of 4D printing materials and technology is the future.

Additive manufacturing technology is still discovering new applications, new materials, and new processes. Further research is required to overcome the many challenges that additive manufacturing faces today in the research area of powder manufacturing technologies in 3D printing, pre-and post-processing technologies and approaches, AM processes and optimizations, inspection processes and quality evaluation, new materials for 3D printing, design and simulation in AM, topology optimization, microstructure design, new materials in 3D printing such as silicone, new AM machine design, and development, etc.

Silicone is a relatively new material in additive manufacturing technology—silicone's mechanical properties are ideal for many applications–good thermal stability and chemical resistance, biocompatibility, water tightness, and electrical insulation.

On the other hand, silicone is an elastomer, and unlike thermoplastics, it cannot return to a liquid state after it's been solidified. However, 3D-printed silicone eliminates the model and mold steps completely, and simply prints the final part. This process saves a huge amount of time and cost compared with injection molding.

During the last few years, some companies have developed novel approaches to 3D printing silicone. All approaches that they used produced parts comparable to injection molding. There are many applications for today's 3D-printed silicone parts and products such as silicone seals, joints, hearing aids, prosthetics, dampers & bellows, fabrication of functional prototypes, custom parts, etc., which would not be economically feasible using injection molding.

However, 3D printing silicone comes with challenges. As mentioned earlier, silicone is an elastomer, once solidified, cannot be melted down like thermoplastics which can be melted and returned to a solid state. Moreover, silicones are highly resistant to UV light and cannot be cured easily in their pure form.

The above discussions reveal that silicone requires special 3D printing machines and processes. The main objective of the first part of this research is to design and develop a 3D silicone printing machine (3D SPM) tailored to the silicone material. Innovative transdisciplinary integrated design tools will be used for the 3D SPM preliminary design [6, 7].

2 Materials and Methods

2.1 Transdisciplinary Design Tools Integration

The expected results of Transdisciplinary (TD) research and education emphasize teamwork; bringing together non-academic experts and academic researchers from diverse disciplines; developing and sharing concepts, methodologies, processes, and tools; all to create fresh, stimulating ideas that expand the boundaries of possibilities, and more effectively target real-world problems. The TD approach teaches students to seek collaboration outside the bounds of their professional experience to make new discoveries, explore different perspectives, express and exchange ideas, and gain new insights [8].

Transdisciplinary (TD) tools used in this study have been applied in many fields including product development, project management, many engineering disciplines, design of the organization, sustainable development, social issues, environmental issues, and others across many industries including automotive, aerospace, telecom, semiconductor, defense, transportation, energy, healthcare, agriculture, and more – the integration of well-known Transdisciplinary tools such as Quality Function Deployment (QFD), House of Quality (HOQ), TRIZ, Interpretive Structural Modeling (ISM), Design Structure Matrix (DSM), and Axiomatic Design (AD) addressing a wide range of domains will be used for this research.

Integration of some of the design tools mentioned above has been discussed by other researchers. Based on the design process outlined by Pahl et al. [9], the integration of HOQ and TRIZ was discussed by Mayda and Borklu [10]. Zheng et al. [11] took a similar approach to the integration of these same tools and they used the resulting output of integration as input for the Data Envelopment Analysis (DEA). A study trying to address the issue of improving the designs of temporary housing for refugees in rural areas through the integration of QFD and AD has been proposed by Gilbert et al. [12]. Several other research papers have been written on the integration of AD and TRIZ design tools. Tian et al. developed "an integrated model of these two methods to increase the efficiency and quality of the problem-solving process for conceptual design" [13]. The expansion of integration of TRIZ, AD, and QFD tools for energy savings design was presented by Runliang and Hui [14]. Furthermore, Wang et al. [15] proposed the integration of TRIZ, DSM, and ISM for concept design in a product development process.

This research paper will extend the previous integration approaches discussed above as illustrated in Figure 1 [16, 17]. The methodology shown in Figure 1 will be followed to design a 3D SPM. As shown in Figure 1, the Kano analysis is a reliable method for assessing customer needs and categorizing them in terms of key groups such as must-have (mandatory) features, optional (performance) features, and indifferent, and attractive features. The KJ Diagram is used to cluster and prioritize customer needs. The CTQ is used to explore the quantitative specifications of a product. QFD/HOQ is a mapping method that relates customer requirements to engineering characteristics [18, 19]. TRIZ is a toolset discovered by Russian researchers for creative problem solving that provides a systematic approach to solving contradictions in engineering characteristics. The ISM is a systematic approach that identifies directional relationships among the factors affecting complex issues. Design Structure Matrix (DSM), also referred to as dependency structure matrix, is a tool for managing complexity [20].

2.2 Kano Analysis–understanding Customer Needs

The *Kano Model* is a method used for product development and customer satisfaction that was proposed in the 1980s by Professor Noriaki Kano. Following the Kano model, in order to eliminate inconsistency and discover customer requirements, 12 positive and 12 negative survey questions were created. Then the questionnaire is sent to a group of prospective customers and we received 42 responses (see Table A1 in Appendix A). To translate the survey results, the category of each attribute is classified through Kano's paired functional/dysfunctional questionnaire as shown in Figure 2.

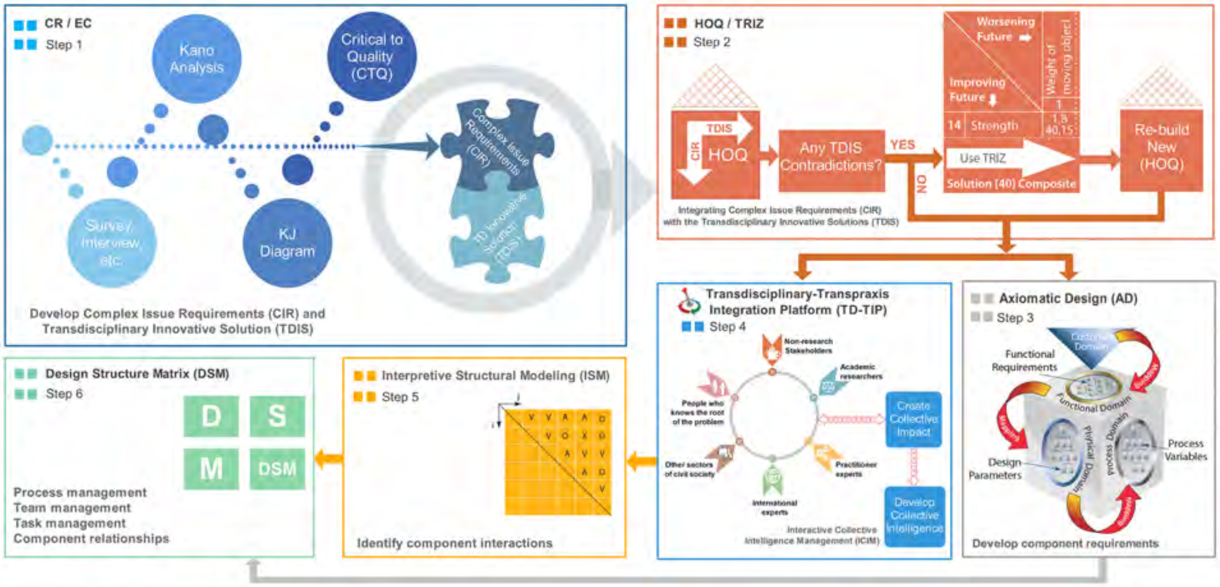
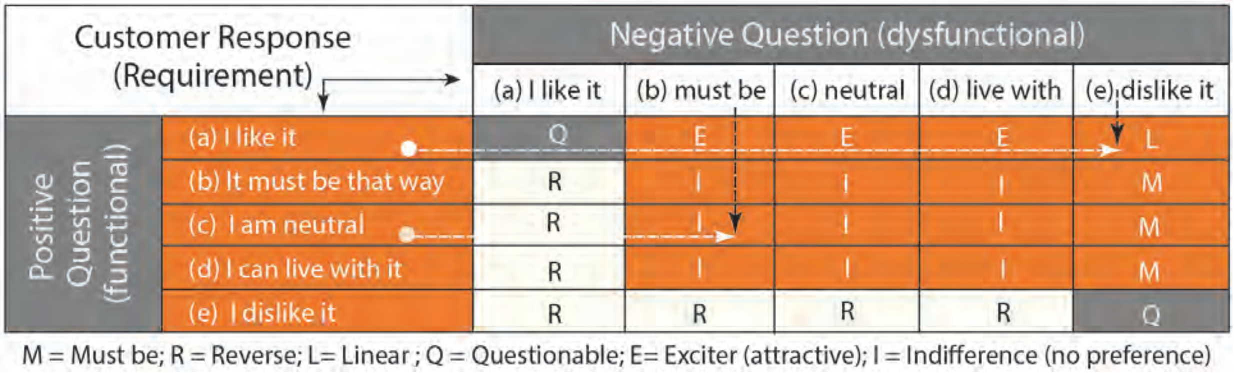


Figure 1: Integrated transdisciplinary tools for complex problem solutions (Ertas, lecture notes)



Customer Response (Requirement)		Negative Question (dysfunctional)				
		(a) I like it	(b) must be	(c) neutral	(d) live with	(e) dislike it
Positive Question (functional)	(a) I like it	Q	E	E	E	L
	(b) It must be that way	R	I	I	I	M
	(c) I am neutral	R	I	I	I	M
	(d) I can live with it	R	I	I	I	M
	(e) I dislike it	R	R	R	R	Q

M = Must be; R = Reverse; L= Linear ; Q = Questionable; E= Exciter (attractive); I = Indifference (no preference)

Figure 2: Integrated transdisciplinary tools for complex problem solutions (Ertas, lecture notes)

Using survey results and Figure 2, each positive question was compared against each negative question for every respondent to determine the appropriate letters shown in Table 1. To develop a set of customer requirements, qualitative data collected from customers is used to build the KJ diagram shown in Figure 3. The KJ-Method is a useful tool used to organize data and ideas.

2.3 Critical to Quality Characteristics

Once the customer requirements are known, an effort is made to translate them into quantitative terms known as Critical to Quality (CTQ) characteristics. CTQs are the key measurable characteristics of a product that help translate the most important needs of products into requirements to ensure their quality. In general, a CTQ is translated from a qualitative customer statement to a quantitative product specification. The CTQ tree which consists of four elements (need, drivers, requirements, and convert requirements into CTQs) for the 3D SPM is shown in Figure 4.

Table 1. Kano analysis results for 42 responses.

Features	E	L	M	I	R	Q
Small size	17	4	0	11	2	8
Low Cost	14	14	7	6	0	1
High Accuracy	6	19	12	4	0	1
Low Noise	13	17	5	3	2	2
High Sanitation	1	22	6	11	1	1
Fast Printing	17	11	2	10	1	1
Color Options	19	11	5	4	1	2
High Reliability	4	21	12	3	1	1
Printing different Materials	15	15	6	4	1	1
Low maintenance	8	17	5	7	4	1
Easy Transport	14	16	4	6	1	1
Automation	12	18	6	4	1	1
High Wear Resistance	7	16	9	5	2	8

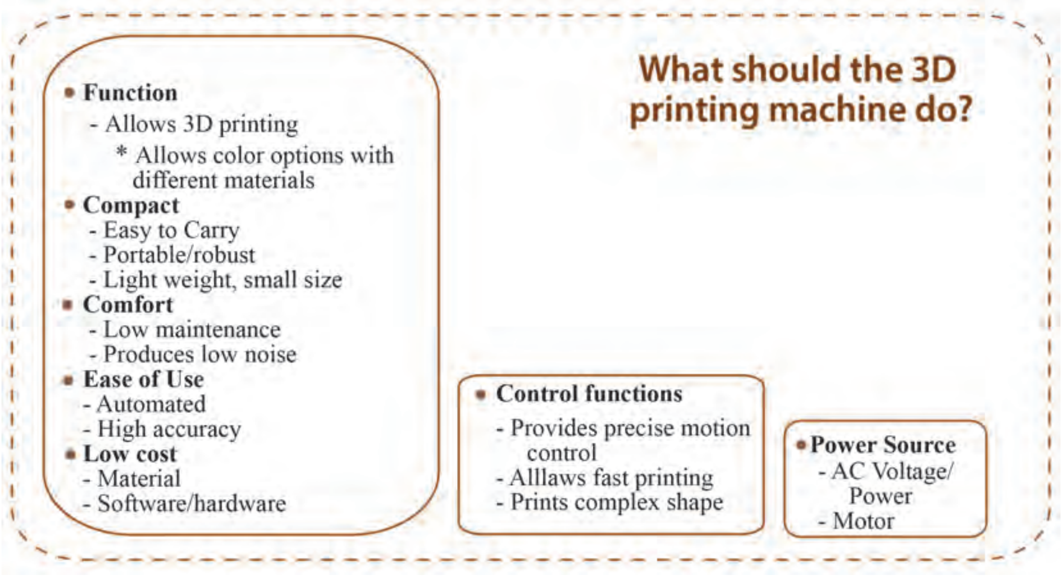


Figure 3: *KJ diagram for 3D printing machine.*

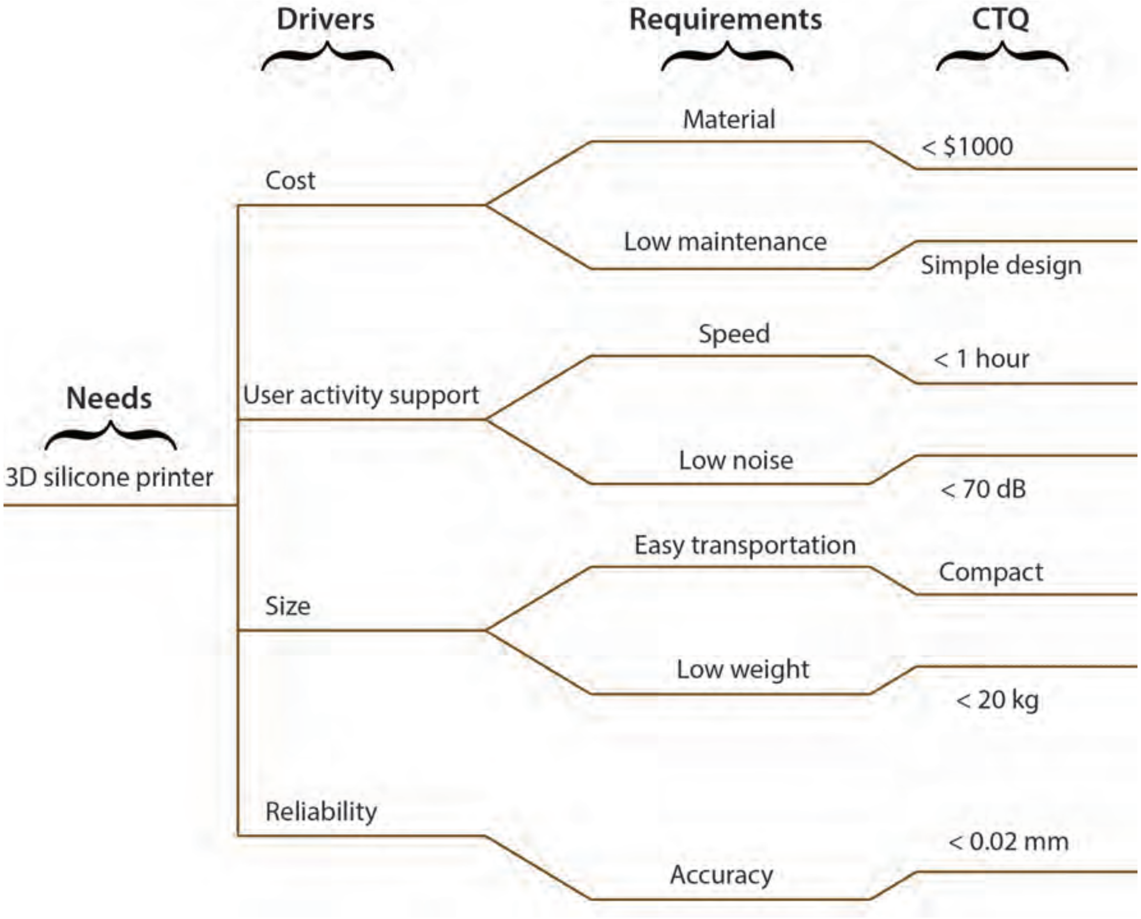


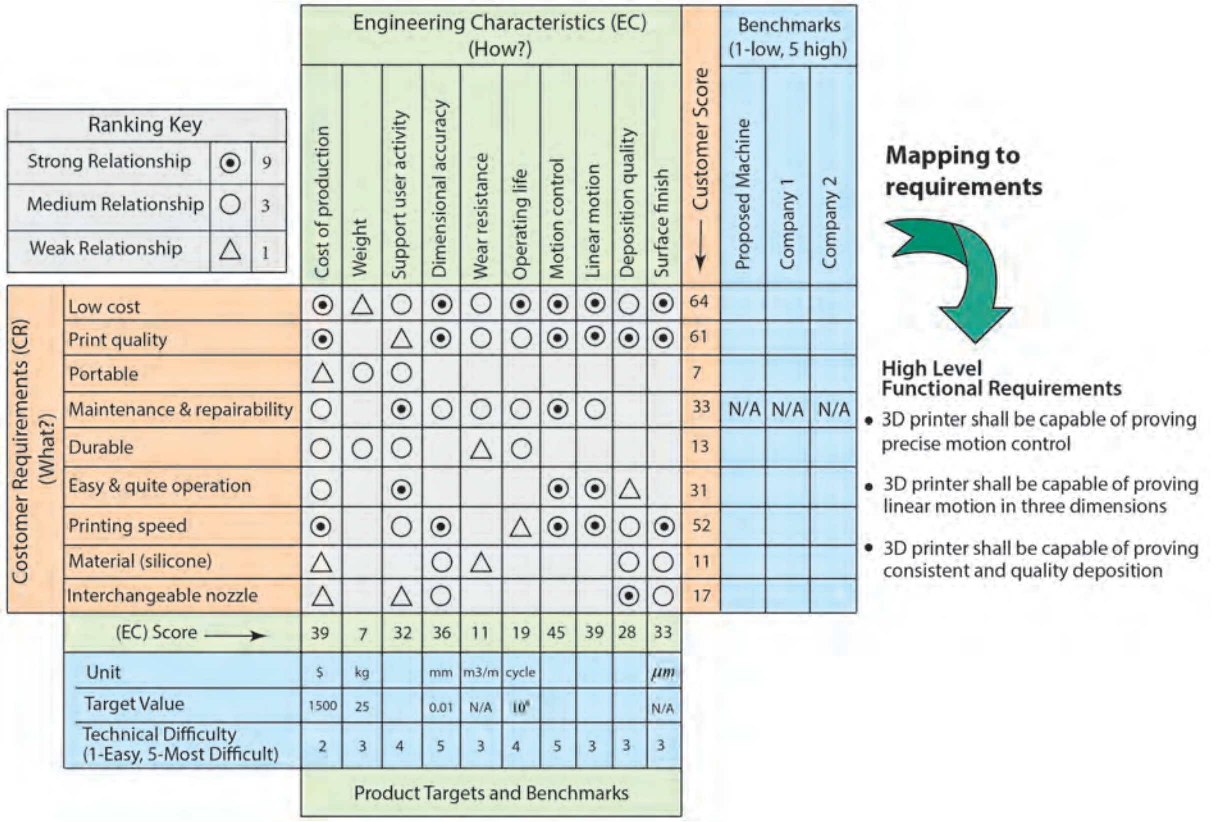
Figure 4: *CTQ tree for 3D printing machine.*

3 Quality Function Deployment (QFD)

QFD requirement prioritization method and management approach for product development to consider the voice of the customer – to weigh or prioritize customer requirements and correlate customer desires (WHATs) to engineering characteristics (HOWs). It is a method for identifying customer needs and making sure that the voice of the customer is included in a design process for product development.

The five stages of the QFD chart for the 3D SPM (customer requirements, engineering characteristics, relationships matrix, benchmarks, and product targets) are shown in Figure 5. As shown in Figure 5, the customer's requirements are listed as the row of the matrix, and the engineering characteristics are listed as the columns of the matrix. Engineering characteristics are what designers control. A ”target value” refers to the planned value for an ”engineering characteristic” in the final design that you have certain control over. For example, for the 3D printing machine, the target value for the cost of the product is determined to be approximately $1500, weight is 25 kg, dimensional accuracy is 0.01 mm, and the operating life is set to approximately 10^6 cycles.

By grading the relationships matrix as strong, medium, and weak between the customer's requirements and engineering characteristics we discover those areas in need of improvement. As shown in Figure 5, low cost (64), print speed (52)), and print quality (61) scored the highest for the customer's requirements. Cost of production (39), linear motion (39), and motion control (45) scored the highest for engineering characteristics. Our design efforts focused on the improvement of those areas that scored high. The cost



Ranking Key		
Strong Relationship	⦿	9
Medium Relationship	○	3
Weak Relationship	△	1

Costomer Requirements (CR) (What?)	Cost of production	Weight	Support user activity	Dimensional accuracy	Wear resistance	Operating life	Motion control	Linear motion	Deposition quality	Surface finish	Customer Score	Proposed Machine	Company 1	Company 2
Low cost	⦿	△	○	⦿	○	⦿	⦿	⦿	○	⦿	64			
Print quality	⦿		△	⦿	○	○	⦿	⦿	⦿	⦿	61			
Portable	△	○	○								7			
Maintenance & repairability	○		⦿	○	○	○	⦿	○			33	N/A	N/A	N/A
Durable	○	○	○		△	○					13			
Easy & quite operation	○		⦿				⦿	⦿	△		31			
Printing speed	⦿		○	⦿		△	⦿	⦿	○	⦿	52			
Material (silicone)	△			○	△				○	○	11			
Interchangeable nozzle	△		△	○					⦿	○	17			
(EC) Score →	39	7	32	36	11	19	45	39	28	33				
Unit	$	kg		mm	m3/m	cycle				μm				
Target Value	1500	25		0.01	N/A	10^6				N/A				
Technical Difficulty (1-Easy, 5-Most Difficult)	2	3	4	5	3	4	5	3	3	3				

High Level Functional Requirements

- 3D printer shall be capable of proving precise motion control
- 3D printer shall be capable of proving linear motion in three dimensions
- 3D printer shall be capable of proving consistent and quality deposition

Figure 5: *QFD for 3D printing machine.*

of a 3D SPM is the driving factor for this product to survive in the market. Since benchmarks for other competitors were not available, we left this part of the QFD blank. Finally, the target difficulties are shown in the figure. Note that, surface finish will not be difficult to achieve for silicone printing therefore difficulty is set as 3. As seen from Figure 5, both customer requirements and engineering characteristics provided us with the following high-level functional requirements for the 3D SPM:

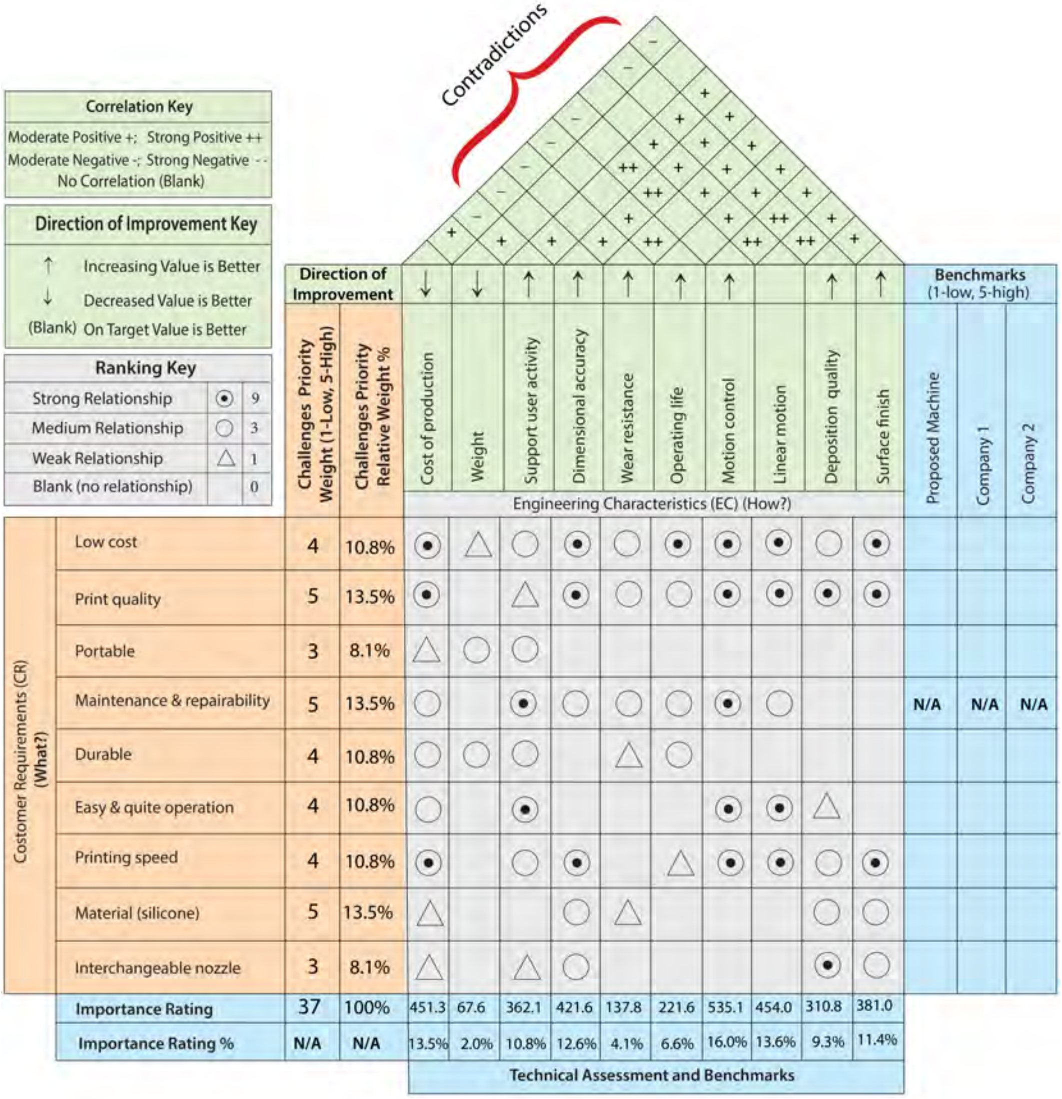
- 3D printer shall be capable of proving precise motion control,
- 3D printer shall be capable of proving linear motion in three dimensions, and
- 3D printer shall be capable of proving consistent and quality deposition.

The above functional requirements will be used for the axiomatic design part of this paper to select the 3D SPM components.

4 House of Quality (HOQ)

The house of quality is a transdisciplinary design tool that has been used successfully by Japanese manufacturers of consumer electronics, home appliances, clothing, integrated circuits, synthetic rubber, construction equipment, agricultural engines, etc.

Figure 6 shows the 3D SPM HOQ. The HOQ matrix has the shape of a house with a *correlation matrix* as its roof – Like the QFD, it uses the same relationship matrix to relate the customer requirements to engineering characteristics. As shown in the figure, HOQ provides more information than QFD provides.



Costomer Requirements (CR) (What?)	Challenges Priority Weight (1-Low, 5-High)	Challenges Priority Relative Weight %	Cost of production	Weight	Support user activity	Dimensional accuracy	Wear resistance	Operating life	Motion control	Linear motion	Deposition quality	Surface finish	Proposed Machine	Company 1	Company 2
Direction of Improvement			↓	↓	↑	↑	↑	↑	↑		↑	↑			
Low cost	4	10.8%	⊙	△	○	⊙	○	⊙	⊙	⊙	○	⊙			
Print quality	5	13.5%	⊙		△	⊙	○	○	⊙	⊙	⊙	⊙			
Portable	3	8.1%	△	○	○										
Maintenance & repairability	5	13.5%	○		⊙	○	○	○	⊙	○			N/A	N/A	N/A
Durable	4	10.8%	○	○	○		△	○							
Easy & quite operation	4	10.8%	○		⊙				⊙	⊙	△				
Printing speed	4	10.8%	⊙		○	⊙		△	⊙	⊙	○	⊙			
Material (silicone)	5	13.5%	△			○	△				○	○			
Interchangeable nozzle	3	8.1%	△		△	○					⊙	○			
Importance Rating	37	100%	451.3	67.6	362.1	421.6	137.8	221.6	535.1	454.0	310.8	381.0			
Importance Rating %	N/A	N/A	13.5%	2.0%	10.8%	12.6%	4.1%	6.6%	16.0%	13.6%	9.3%	11.4%			

Figure 6: *HOQ for 3D printing machine.*

From the HOQ analysis, it is clear that the 3D printing machine 'motion control' has the highest importance rating (16.0%). This critical design point should receive concentrated effort in the design process. The direction of improvement for engineering characteristics is also shown in Figure 6. For example, if we keep all the other engineering characteristics constant, a lower weight is better for the 3D SPM design.

The engineering characteristics may often conflict with each other. As shown in Figure 6, the correlation matrix is used to identify where engineering characteristics support or conflict with each other in the design of the 3D SPM. For example, Figure 6 shows that a 3D SPM with lightweight requires lower-cost production – affects each other positively. Similarly, 'wear resistance' and 'operating life' affect each other strongly positively. But the cost of production and higher dimensional accuracy affects each other negatively – the 3D SPM performs better with a high-quality control system (improvement: good), but the cost of production increases (worsening: bad). This situation involves a trade-off between different engineering characteristics – how much one design parameter can be optimized without sacrificing other parameters. Another option to eliminate the conflict is the use of the "Theory of Inventive Problem Solving (TRIZ)".

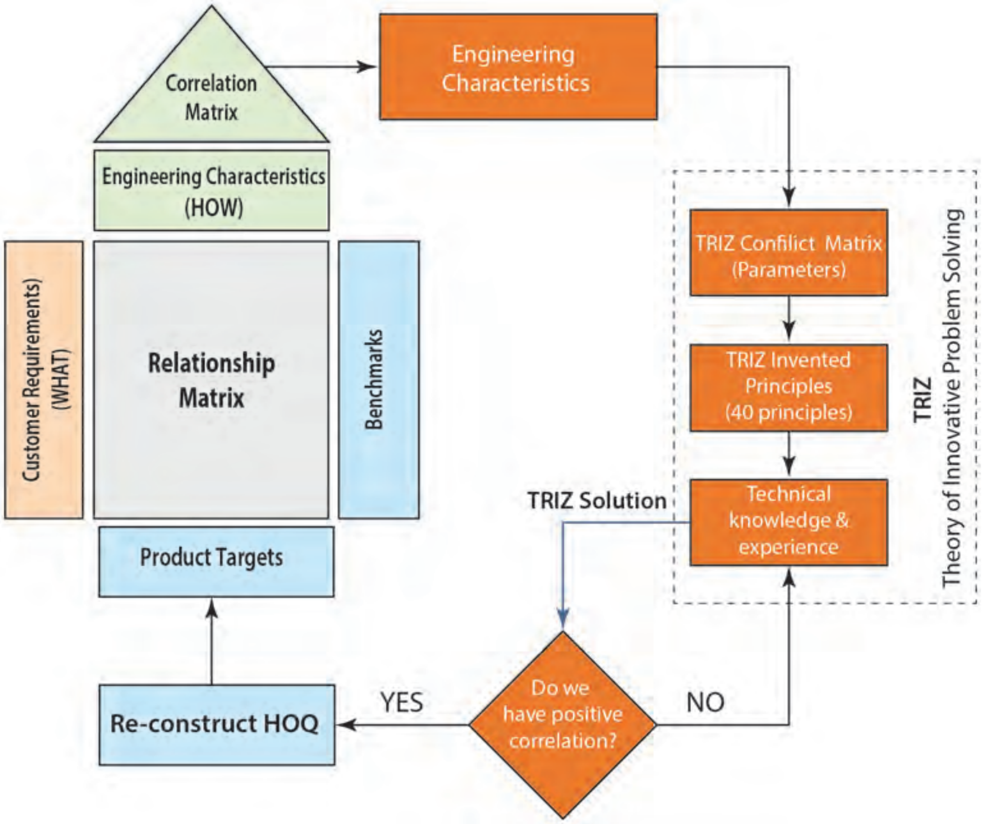


Figure 7: *TRIZ problem solving process.*

5 Theory of Inventive Problem Solving (TRIZ)

Theory of Inventive Problem Solving (TRIZ) developed by G.S. Altshuller and his colleagues in Russia between 1946 and 1985 is a well-known effective methodology to solve complex problems.

"The Russian engineer and scientist Genrikh Altshuller studied thousands of patents and noticed certain patterns. From these patterns, he discovered that the evolution of a technical system is not a random process, but is governed by certain objective laws. These laws can be used to consciously develop a system along its path of technical evolution - by determining and implementing innovations." [21].

After Altshuller evaluated hundreds of thousands of patents to determine the patterns that predict innovative solutions to problems, he found that 99.7 percent of inventions were made using known methods of solution, and only 0.3 percent of solutions were disruptive. One of the important principles of TRIZ is, that instead of quickly jumping to a solution, TRIZ proposes to analyze a problem, build its model, and apply a relevant pattern of a solution from the TRIZ databases to discover possible solution directions.

TRIZ allows design teams to find examples of how people have solved similar problems in the past. In other words, somebody, somewhere, has already solved your problem or one related to it. Creativity means finding that solution and altering it to your problem.

5.1 TRIZ Problem Solving Process

The steps for finding solutions for conflicting problems that exist in the HOQ with TRIZ are the following (see Figure 7)

1. Identify the conflicting engineering characteristics (EC) with negative correlation in the HOQ correlation matrix.
2. Identify the EC's type, which one is improving and which one is worsening characteristics.
3. Replace the ECs with corresponding parameters from TRIZ 39 contradiction matrix.
4. Using the contradiction matrix tables, identify which of the 40 inventive principles are applicable to your problem to resolve the contradiction.
5. After brainstorming, adapt the appropriate solution from 40 inventive principles to resolve the conflict among the ECs in the HOQ correlation matrix.
6. Re-construct the HOQ with the new ECs.

The HOQ shown in Figure 6 identifies relationships among requirements and interactions between the engineering characteristics of the 3D SPM. As seen from this figure, it has negative correlations between ECs of "cost of production" and the other ECs besides the weight. Following the process shown in Figure 7, let's consider the improving characteristic to be the "motion control" and the worsening characteristic to be the "production cost". In other words, If we want to improve the "control system" it will cost more money and time.

Cost reduction is a common topic throughout the industry. However, the TRIZ contradiction matrix does not deal with cost explicitly. Darrell Mann (2004) suggested some of the same parameters used in the TRIZ matrix that cause costs to increase [22]. They are:

- Complexity of the system
- Complexity of control
- System-generated harmful factors
- Time and risk issues for the R&D, production, supply, and support
- Speed of a process
- Duration of action
- Loss of energy, loss of material, loss of information, loss of time
- Reliability
- System-generated harmful factors
- Ease of operation
- Ease of manufacturing
- Ease of repair
- System complexity
- Extent of automation
- Productivity

Using the above list of parameters to comprehend what causes the 3D SPM cost to increase, we adopted "complexity of device (36)" as a worsening characteristic, and for "motion control" we adopted "Reliability (27)" as an improving characteristic. From the TRIZ matrix of contradictions (see Table A2 in Appendix), at the intersection of the two characteristics (see Figure 8) the following three potential solutions principles (see Table A3 in Appendix) are possible: (13) Inversion, (35) Parameter change, and (1) Segmentation.

Decision: Among the other three suggested solutions, "Segmentation (1)" will lead to a solution. As per the segmentation definition, we decided to have the 3D SPM modular. This will minimize the cost of repair–maintaining each module independently and also allowing easy upgrades. 3D SPM will be produced cheaply due to saved time and less building material (reducing the 3D printer weight).

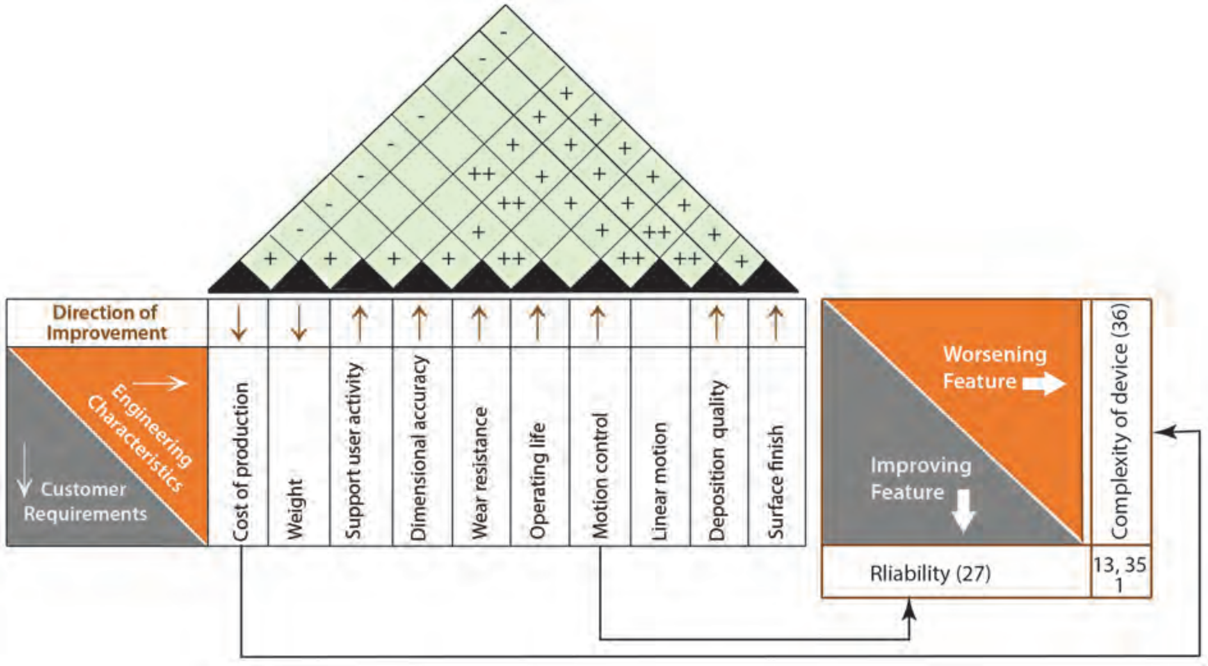


Figure 8: *TRIZ potential principles solutions for contradicting 3D SPM engineering characteristics.*

Note that replacing "cost of production" with "modular design" will eliminate all the other contradictions. The new rebuild HOQ is shown in Figure 9. HOQ shows the relationships among the engineering characteristics but does not show the directional relationships. Interpretive Structural Modeling (ISM) will help us to see how the engineering characteristics will interact and affect each other (directional relationships) [23].

6 Integrating Re-built HOQ with Interpretive Structural Modeling (ISM)

Engineering characteristics from the rebuilt HOQ were used as the factors (parameters) affecting the performance of the 3D SPM as input for Interpretive Structural Modeling (see Figure 10).

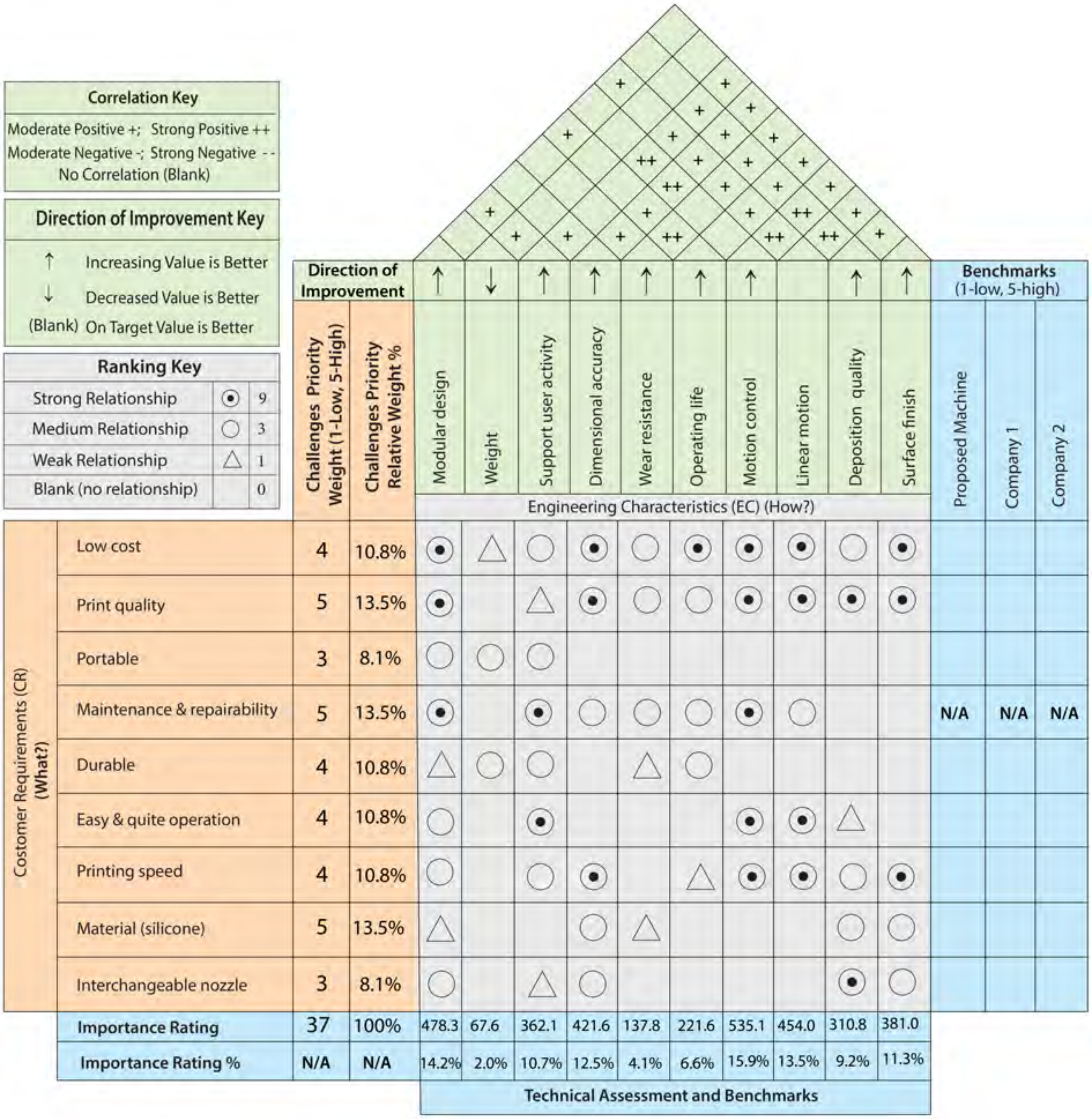
Interpretive Structural Modeling (**ISM**) is an effective methodology used to cope with the novel, ill-defined problems in complex, real-world settings. It is a transdisciplinary tool used to understand complex situations that occur in diverse knowledge domains such as: when developing plans, managing organizations, designing large-scale systems, and complex product development [24].

Transdisciplinary collective intelligence is a new mode of information gathering, knowledge creation, and decision-making that draws on expertise from a wider range of organizations (academic or non-academic) and collaborative partnerships [25, 26].

The sequence of activities to develop an interpretive structural model is shown in Figure 10 [7]. Note that the the sequence of these activities may change from one application to another.

6.1 Structural Self-Interaction Matrix

After identifying the factors (parameters), the next step was to establish a contextual relationship between the factors (see Figure 11(c)). During this phase, the transdisciplinary collective intelligence workshop



Costomer Requirements (CR) (What?)	Challenges Priority Weight (1-Low, 5-High)	Challenges Priority Relative Weight %	Modular design	Weight	Support user activity	Dimensional accuracy	Wear resistance	Operating life	Motion control	Linear motion	Deposition quality	Surface finish	Proposed Machine	Company 1	Company 2
Direction of Improvement			↑	↓	↑	↑	↑	↑	↑		↑	↑			
Low cost	4	10.8%	⊙	△	○	⊙	○	⊙	⊙	⊙	○	⊙	N/A	N/A	N/A
Print quality	5	13.5%	⊙		△	⊙	○	○	⊙	⊙	⊙	⊙			
Portable	3	8.1%	○	○	○										
Maintenance & repairability	5	13.5%	⊙		⊙	○	○	○	⊙	○					
Durable	4	10.8%	△	○	○		△	○							
Easy & quite operation	4	10.8%	○		⊙				⊙	⊙	△				
Printing speed	4	10.8%	○		○	⊙		△	⊙	⊙	○	⊙			
Material (silicone)	5	13.5%	△			○	△				○	○			
Interchangeable nozzle	3	8.1%	○		△	○					⊙	○			
Importance Rating	37	100%	478.3	67.6	362.1	421.6	137.8	221.6	535.1	454.0	310.8	381.0			
Importance Rating %	N/A	N/A	14.2%	2.0%	10.7%	12.5%	4.1%	6.6%	15.9%	13.5%	9.2%	11.3%			

Figure 9: *Rebuild HOQ.*

participants (one faculty member, one Ph.D. student, and five undergraduate students) decided upon the pairwise relationship between the factors affecting 3D SPM performance.

The four symbols used to indicate the direction of the relationship between the factors i and j are given below:

- V = for the relation from column (i) to row (j) but not in both directions;
- A = for the relation from the row (j) to column (i) but not in both directions;
- X = for both-direction relations: from column (i) to row (j) and from the row (j) to column (i); and

- O= if there are no relationships between factors

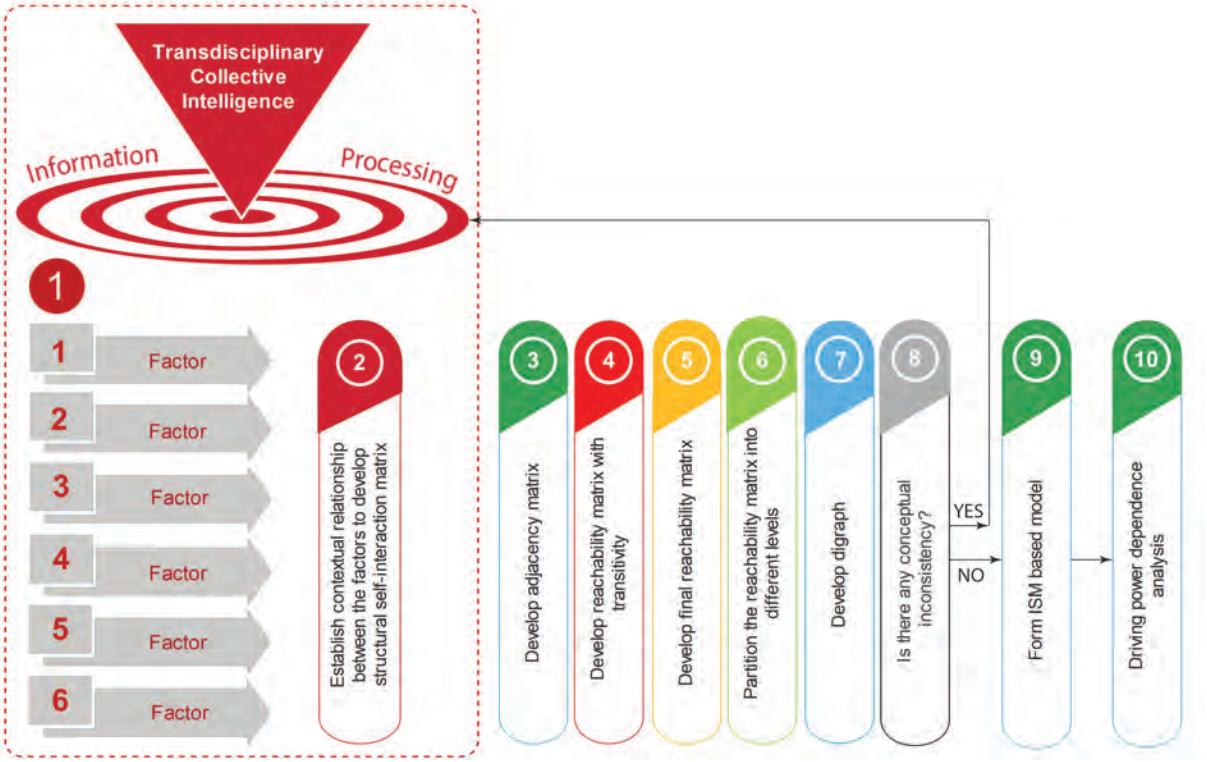


Figure 10: *ISM process (Ertas and Gulbulak, 2021, [7]).*

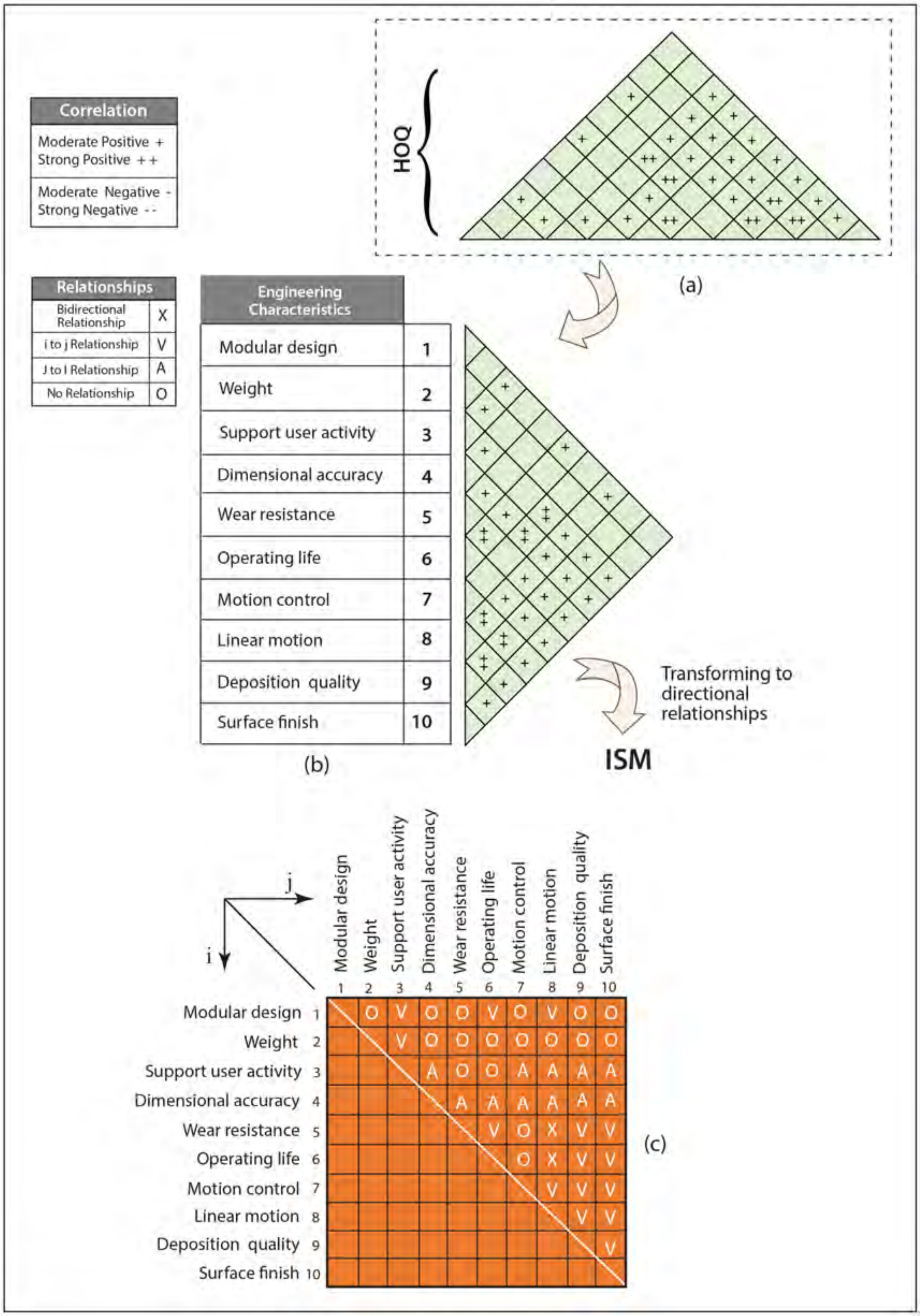
6.2 Adjacency Matrix

The adjacency matrix, R_a shown in Figure 12 was developed by transforming SSIM into a binary matrix by substituting V, A, X, and O with 1 and 0.

- When the (i, j) entry in the SSIM is V, then the (i, j) entry in the reachability matrix becomes 1 and the (j, i) entry becomes 0.
- When the (i, j) entry in the SSIM is A, then the (i, j) entry in the reachability matrix becomes 0 and the (j, i) entry becomes 1.
- when the (i, j) entry in the SSIM is X, then both the (i, j) and (j, i) entries of the reachability matrix become 1.
- when the (i, j) entry of the SSIM is O, then both the (i, j) and (j, i) entries of the reachability matrix become 0.

6.3 Reachability Matrix with Transitivity

Then, the reachability matrix with transitivity shown in Figure 13 was developed. The reachability matrix is tested for the transitivity rule and is updated until transitivity is confirmed. The transitivity rule is "if **A** has a relationship to **B** and **B** has a relationship to **C**, then **A** has a relationship to **C**".



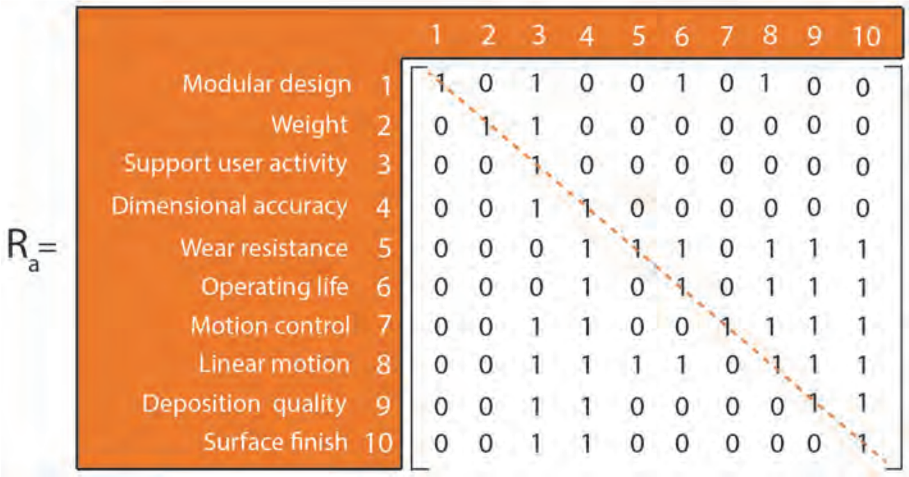
Correlation
Moderate Positive +
Strong Positive ++
Moderate Negative -
Strong Negative - -

Relationships	
Bidirectional Relationship	X
i to j Relationship	V
J to I Relationship	A
No Relationship	O

Engineering Characteristics	
Modular design	1
Weight	2
Support user activity	3
Dimensional accuracy	4
Wear resistance	5
Operating life	6
Motion control	7
Linear motion	8
Deposition quality	9
Surface finish	10

	Modular design 1	Weight 2	Support user activity 3	Dimensional accuracy 4	Wear resistance 5	Operating life 6	Motion control 7	Linear motion 8	Deposition quality 9	Surface finish 10
Modular design 1		O	V	O	O	V	O	V	O	O
Weight 2			V	O	O	O	O	O	O	O
Support user activity 3				A	O	O	A	A	A	A
Dimensional accuracy 4					A	A	A	A	A	A
Wear resistance 5						V	O	X	V	V
Operating life 6							O	X	V	V
Motion control 7								V	V	V
Linear motion 8									V	V
Deposition quality 9										V
Surface finish 10										

Figure 11: *Maping HOQ to ISM-SSIM.*



$R_a =$

		1	2	3	4	5	6	7	8	9	10
Modular design	1	1	0	1	0	0	1	0	1	0	0
Weight	2	0	1	1	0	0	0	0	0	0	0
Support user activity	3	0	0	1	0	0	0	0	0	0	0
Dimensional accuracy	4	0	0	1	1	0	0	0	0	0	0
Wear resistance	5	0	0	0	1	1	1	0	1	1	1
Operating life	6	0	0	0	1	0	1	0	1	1	1
Motion control	7	0	0	1	1	0	0	1	1	1	1
Linear motion	8	0	0	1	1	1	1	0	1	1	1
Deposition quality	9	0	0	1	1	0	0	0	0	1	1
Surface finish	10	0	0	1	1	0	0	0	0	0	1

Figure 12: *Adjacency matrix.*

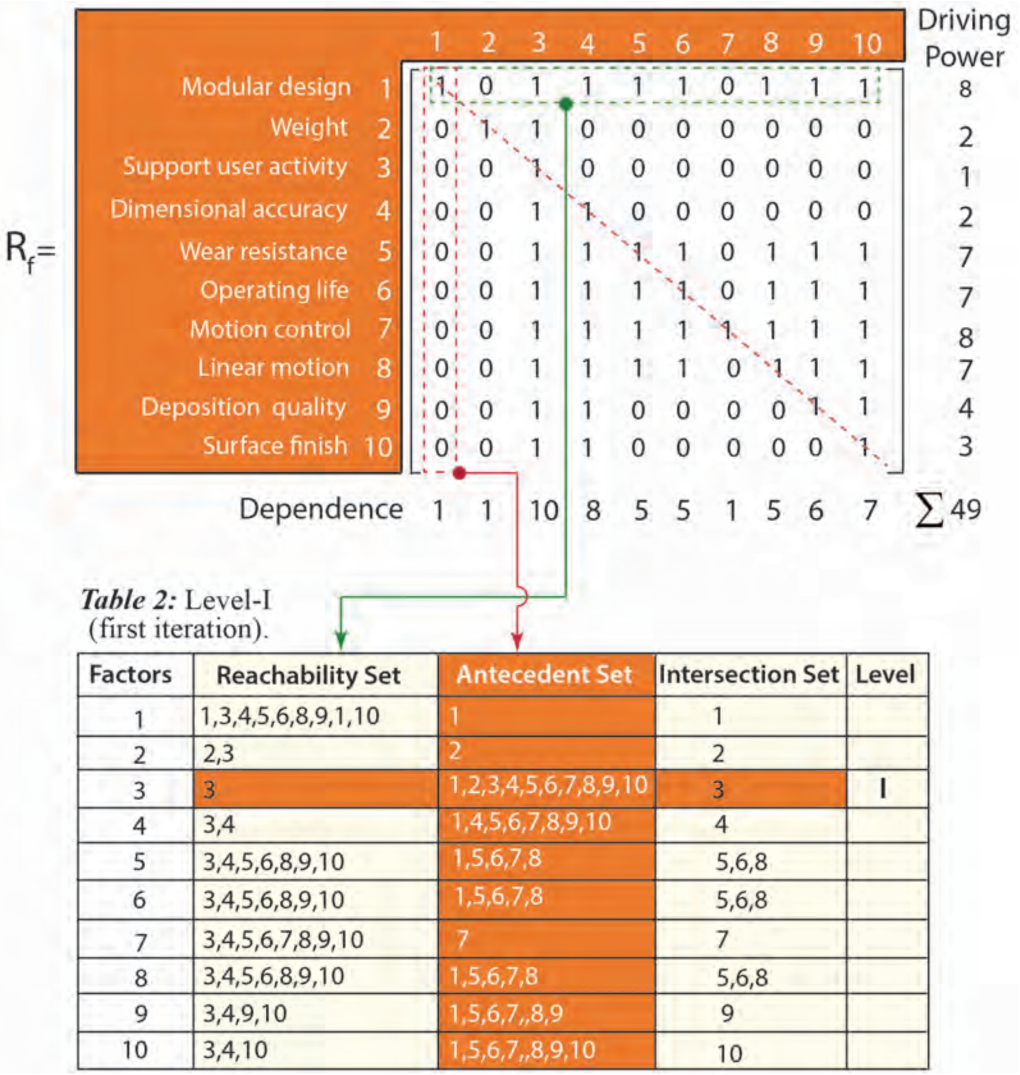
$R_f =$

		1	2	3	4	5	6	7	8	9	10	Driving Power
Modular design	1	1	0	1	1	1	1	0	1	1	1	8
Weight	2	0	1	1	0	0	0	0	0	0	0	2
Support user activity	3	0	0	1	0	0	0	0	0	0	0	1
Dimensional accuracy	4	0	0	1	1	0	0	0	0	0	0	2
Wear resistance	5	0	0	1	1	1	1	0	1	1	1	7
Operating life	6	0	0	1	1	1	1	0	1	1	1	7
Motion control	7	0	0	1	1	1	1	1	1	1	1	8
Linear motion	8	0	0	1	1	1	1	0	1	1	1	7
Deposition quality	9	0	0	1	1	0	0	0	0	1	1	4
Surface finish	10	0	0	1	1	0	0	0	0	0	1	3
Dependence		1	1	10	8	5	5	1	5	6	7	$\sum$ 49

Figure 13: *Reachability matrix with transivity.*

6.4 Level Partitioning

The driving force and dependence obtained from the final reachability matrix were used to classify the parameters into groups as shown in Tables 2 through 7. Figure 14 shows how to develop Table 2 which provides the Level-I of the first iteration–using rows of R_f to identify the "Reachability Sets" and using columns to identify the "Antecedent Set". The same proses is used to develop the remaining tables. The intersection of antecedent sets and reachability sets will provide an intersection set. In other words, the factors common in the reachability set and the antecedent set are included in the intersection set. When the factors of the intersection and reachability sets are the same, then that factor will be identified as the top-level group (level I group) in the ISM hierarchy. Once the top-level factors are identified, they are deleted from the set to identify the next level. As seen in Tables 2 through 7, this iteration process is repeated until all the levels are identified. These levels will be used to build the digraph and ISM model.



$$R_f = \begin{array}{lc|cccccccccc|c}
 & & 1 & 2 & 3 & 4 & 5 & 6 & 7 & 8 & 9 & 10 & \text{Driving Power} \\
\hline
\text{Modular design} & 1 & 1 & 0 & 1 & 1 & 1 & 1 & 0 & 1 & 1 & 1 & 8 \\
\text{Weight} & 2 & 0 & 1 & 1 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 2 \\
\text{Support user activity} & 3 & 0 & 0 & 1 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 1 \\
\text{Dimensional accuracy} & 4 & 0 & 0 & 1 & 1 & 0 & 0 & 0 & 0 & 0 & 0 & 2 \\
\text{Wear resistance} & 5 & 0 & 0 & 1 & 1 & 1 & 1 & 0 & 1 & 1 & 1 & 7 \\
\text{Operating life} & 6 & 0 & 0 & 1 & 1 & 1 & 1 & 0 & 1 & 1 & 1 & 7 \\
\text{Motion control} & 7 & 0 & 0 & 1 & 1 & 1 & 1 & 1 & 1 & 1 & 1 & 8 \\
\text{Linear motion} & 8 & 0 & 0 & 1 & 1 & 1 & 1 & 0 & 1 & 1 & 1 & 7 \\
\text{Deposition quality} & 9 & 0 & 0 & 1 & 1 & 0 & 0 & 0 & 0 & 1 & 1 & 4 \\
\text{Surface finish} & 10 & 0 & 0 & 1 & 1 & 0 & 0 & 0 & 0 & 0 & 1 & 3 \\
\hline
\text{Dependence} & & 1 & 1 & 10 & 8 & 5 & 5 & 1 & 5 & 6 & 7 & \sum 49
\end{array}$$

Table 2: Level-I (first iteration).

Factors	Reachability Set	Antecedent Set	Intersection Set	Level
1	1,3,4,5,6,8,9,1,10	1	1	
2	2,3	2	2	
3	3	1,2,3,4,5,6,7,8,9,10	3	I
4	3,4	1,4,5,6,7,8,9,10	4	
5	3,4,5,6,8,9,10	1,5,6,7,8	5,6,8	
6	3,4,5,6,8,9,10	1,5,6,7,8	5,6,8	
7	3,4,5,6,7,8,9,10	7	7	
8	3,4,5,6,8,9,10	1,5,6,7,8	5,6,8	
9	3,4,9,10	1,5,6,7,,8,9	9	
10	3,4,10	1,5,6,7,,8,9,10	10	

Figure 14: *Identifying level I.*

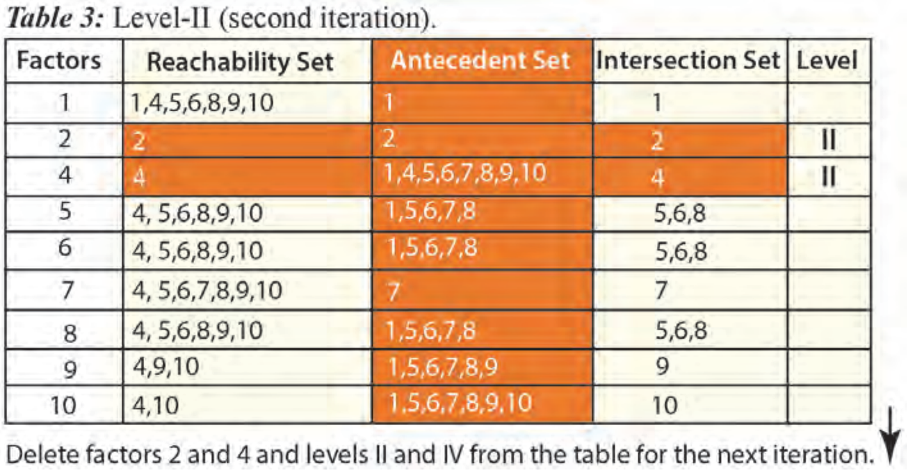
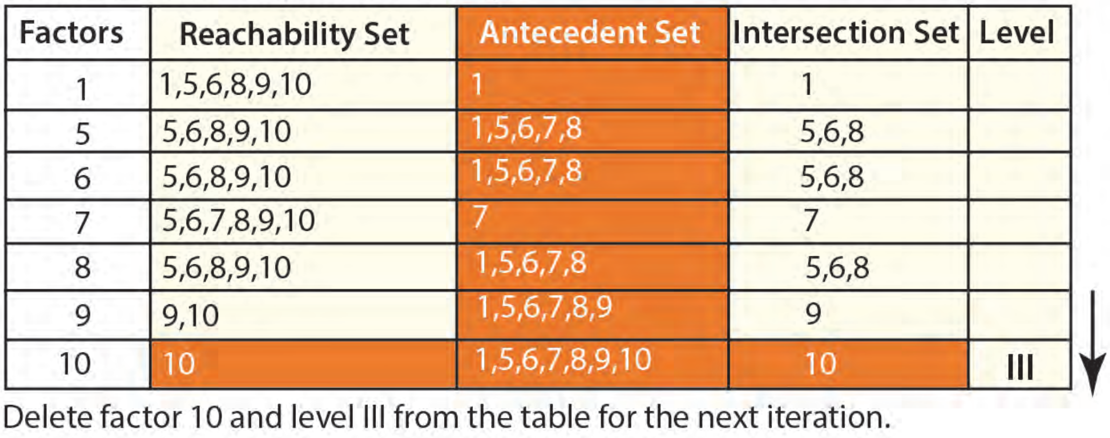


Table 3: Level-II (second iteration).

Factors	Reachability Set	Antecedent Set	Intersection Set	Level
1	1,4,5,6,8,9,10	1	1	
2	2	2	2	II
4	4	1,4,5,6,7,8,9,10	4	II
5	4, 5,6,8,9,10	1,5,6,7,8	5,6,8	
6	4, 5,6,8,9,10	1,5,6,7,8	5,6,8	
7	4, 5,6,7,8,9,10	7	7	
8	4, 5,6,8,9,10	1,5,6,7,8	5,6,8	
9	4,9,10	1,5,6,7,8,9	9	
10	4,10	1,5,6,7,8,9,10	10	

Delete factors 2 and 4 and levels II and IV from the table for the next iteration.

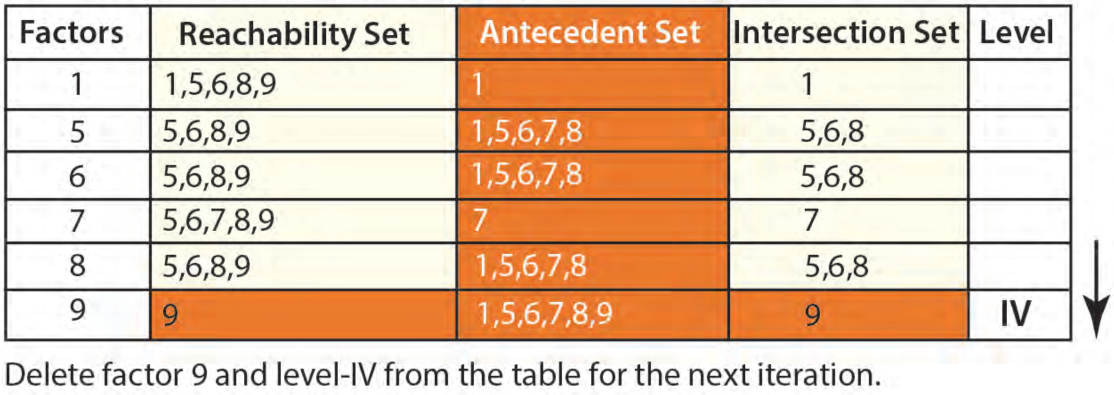
Table 4: Level-III (third iteration).



Factors	Reachability Set	Antecedent Set	Intersection Set	Level
1	1,5,6,8,9,10	1	1	
5	5,6,8,9,10	1,5,6,7,8	5,6,8	
6	5,6,8,9,10	1,5,6,7,8	5,6,8	
7	5,6,7,8,9,10	7	7	
8	5,6,8,9,10	1,5,6,7,8	5,6,8	
9	9,10	1,5,6,7,8,9	9	
10	10	1,5,6,7,8,9,10	10	III

Delete factor 10 and level III from the table for the next iteration.

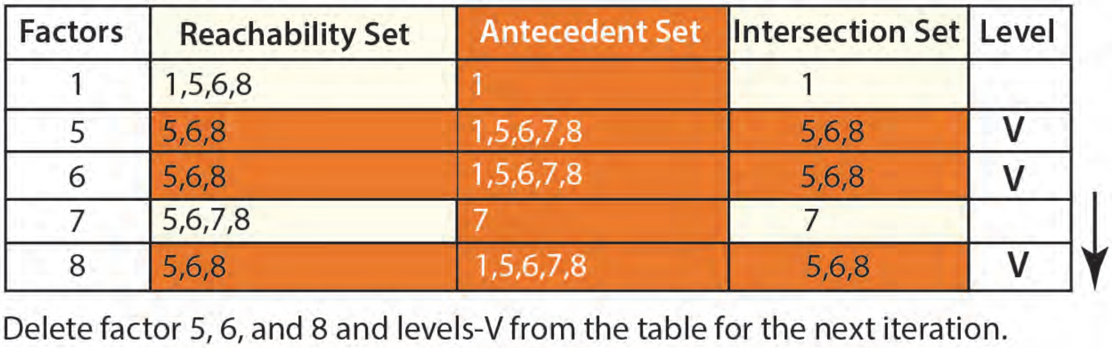
Table 5: Level-IV (fourth iteration).



Factors	Reachability Set	Antecedent Set	Intersection Set	Level
1	1,5,6,8,9	1	1	
5	5,6,8,9	1,5,6,7,8	5,6,8	
6	5,6,8,9	1,5,6,7,8	5,6,8	
7	5,6,7,8,9	7	7	
8	5,6,8,9	1,5,6,7,8	5,6,8	
9	9	1,5,6,7,8,9	9	IV

Delete factor 9 and level-IV from the table for the next iteration.

Table 6: Level-V (fifth iteration).



Factors	Reachability Set	Antecedent Set	Intersection Set	Level
1	1,5,6,8	1	1	
5	5,6,8	1,5,6,7,8	5,6,8	V
6	5,6,8	1,5,6,7,8	5,6,8	V
7	5,6,7,8	7	7	
8	5,6,8	1,5,6,7,8	5,6,8	V

Delete factor 5, 6, and 8 and levels-V from the table for the next iteration.

Table 7: Level-VI (sixth iteration).

Factors	Reachability Set	Antecedent Set	Intersection Set	Level
1	1	1	1	VI
7	7	7	7	VI

6.5 Formation of Digraph

The digraph is a diagram that shows the connections between the direct and indirect relationships between the parameters. As shown in Figure 15, the relationship of parameters and binary associations through matrices can now be translated into graphical form by using the theory of digraphs (directed graphs) [27].

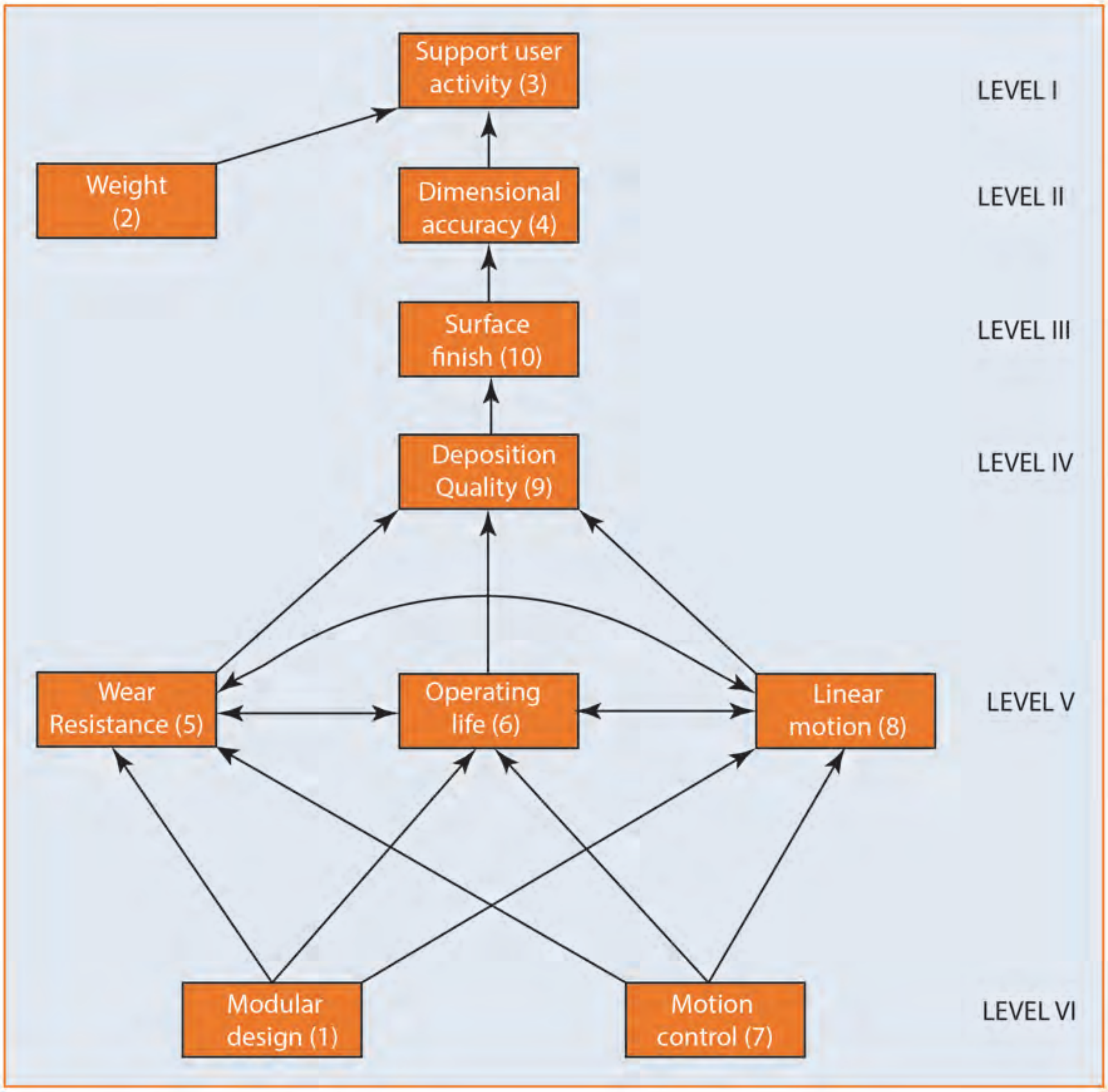


Figure 15: *Digraph of 3D printing machine.*

6.6 MICMAC Analysis:

The MICMAC (Matrice d'Impacts Croisés Multiplication Appliquée á un Classement – cross-impact matrix multiplication applied to classification) analysis was developed by Duperrin and Godet in 1973 to analyze the driving power and the dependence of the parameters affecting the issue in hand [28]. As shown in Figure 16, parameters affecting 3D SPM performance are placed with respect to their driving power and dependence in four clusters: (1) autonomous, (2) dependent, (3) linkage, and (4) independent factors. The

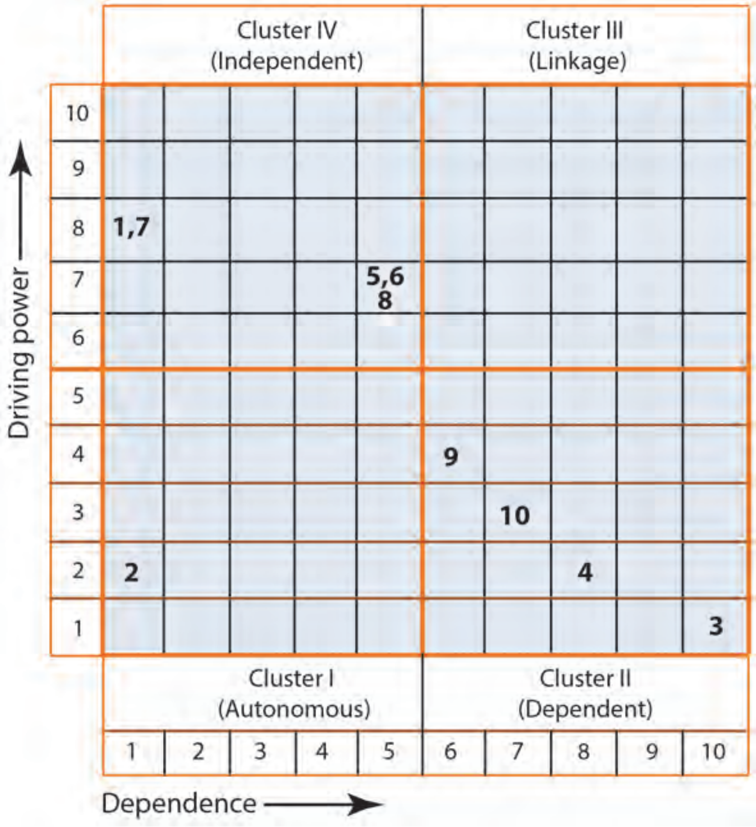


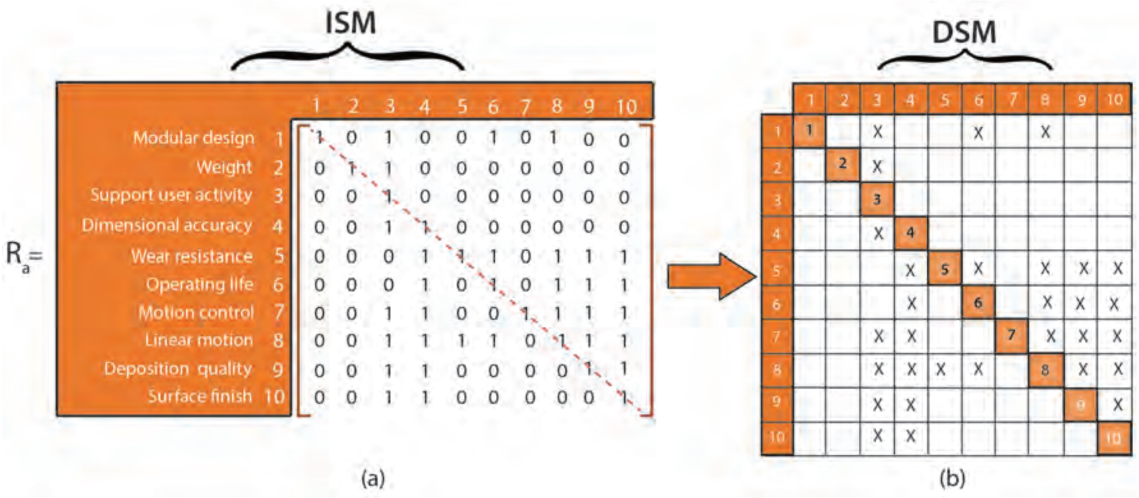
Figure 16: *MICMAC analysis.*

driving power and dependence of each of the parameters are imported from Figure 13. For example, the coordinates of factor 2 are Dependence = 1 and Driving power = 2, thus factor 2 is placed at the very bottom left corner of the MICMAC diagram.

7 Integrating ISM with Design Structure Matrix (DSM)

A transdisciplinary tool called the Design Structure Matrix (DSM), developed by Steward [29] is integrated with ISM and applied to the design of a 3D printing machine. The Design Structure Matrix modeling method is known as a practical tool for modeling design complexities based on interactions [30]. Figure 17 shows the transformation of the adjacency matrix of ISM to DSM. The DSM interactions between ten 3D printing machine parameters are shown in Figure 11(b). In this research, the 3D SPM is modeled to analyze a design process at the level of parameter relationships—A parameter-based DSM that is constructed from a "bottom-up" approach to identify the low-level parameters (describes more specific individual parameters) that define the design: It tracks critical system parameters through the design process to find the sequencing design decisions [31].

As shown in Figure 17(b), the existence of a dependency among the parameters is shown by "X" marks. Note that the DSM uses columns to represent "Provides Information" and rows to represent "Requires Information". In other words, information flows from the column parameter to the row parameter. All the "X" marks above the diagonal in the DSM matrix are called feedback marks and provide required inputs that are not available at the time. Hence, information inputs from the 3D SPM parameters reading down a column of the DSM matrix will be on the base of assumptions. Above the diagonal of DSM (upper



		1	2	3	4	5	6	7	8	9	10
Modular design	1	1	0	1	0	0	1	0	1	0	0
Weight	2	0	1	1	0	0	0	0	0	0	0
Support user activity	3	0	0	1	0	0	0	0	0	0	0
Dimensional accuracy	4	0	0	1	1	0	0	0	0	0	0
Wear resistance	5	0	0	0	1	1	1	0	1	1	1
Operating life	6	0	0	0	1	0	1	0	1	1	1
Motion control	7	0	0	1	1	0	0	1	1	1	1
Linear motion	8	0	0	1	1	1	1	0	1	1	1
Deposition quality	9	0	0	1	1	0	0	0	0	1	1
Surface finish	10	0	0	1	1	0	0	0	0	0	1

	1	2	3	4	5	6	7	8	9	10
1	1		X			X		X		
2		2	X							
3			3							
4			X	4						
5				X	5	X		X	X	X
6				X		6		X	X	X
7			X	X			7	X	X	X
8			X	X	X	X		8	X	X
9			X	X					9	X
10			X	X						10

Figure 17: *Transforming ISM to DSM.*

triangular), marks of feedback or cycles are not desirable – requires time-consuming iterations. For example, parameter 9 (deposition quality) requires information from parameter 10 (surface finish) but, information from parameter 10 has not been made available at that time (see Figure 17 (b)).

The DSM matrix shown in Figure 17 (b) can be manipulated by reordering rows and columns simultaneously to eliminate or reduce the feedback marks in the upper triangle matrix by partitioning [32]. This process allows for better planning of the 3D SPM. Partitioning will allow us to see which parameters will be done in series or in parallel, and to see which ones are coupled so which requires an iterative process for the successful product design based on the system parameters values.

8 Integrating QFD with Axiomatic Design

Axiomatic design (AD) offers discipline-independent representations of a general design process, general principles for effective decision-making, and scalability for complex systems development [33]. AD helps to reduce cost, reduce product development risk, and speed up the marketing of the product [34]. The following two fundamental AD axioms offer a rational basis for the evaluation of given solution alternatives [35].

Independence Axiom

Independence Axiom maintains the independence of the functional requirements – Each functional requirement should be satisfied by its corresponding design parameters without affecting the other functional requirements. In other words, one design parameter satisfies one and only one functional requirement.

Figure 18(a) shows an uncoupled design: each functional requirement is satisfied independently by its corresponding design parameter without affecting the other functional requirements. Figure 18(b) shows a de-coupled design: DP1 is affecting FR1 and FR2 (a triangular matrix). Figure 18(c) represents a coupled design: DP1 affects FR1 and FR2 and similarly, DP2 affects the same functional requirements – the relationship between the design parameters and their functional requirements is circular (coupled).

Information Content Axiom

Minimizes the information content of the design. After satisfying the Independence Axiom, the Information Axiom is used to select the best design among several acceptable design choices. The Information Axiom

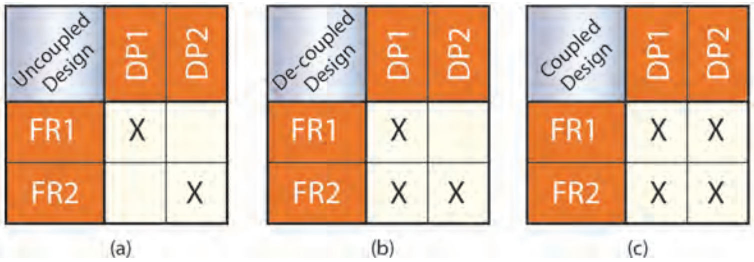


Figure 18: *(a) Uncoupled design, (b) De-coupled design, (c) Coupled design.*

emphasizes design optimization, offering a solution that fully implements the functional requirements with the minimum set of components and interfaces – minimizing the information content of the design.

8.1 Zigzagging and Decomposition

AD methodology suggests that the system design process should start from the high level (abstract) and continue through lower levels of more detail until the point where the system design is defined with enough detail. During every step of the design decisions, the Independence Axiom should not be violated. As shown in Figure 19, the decomposing process is performed by "*zigzagging*" between FR and DP domains.

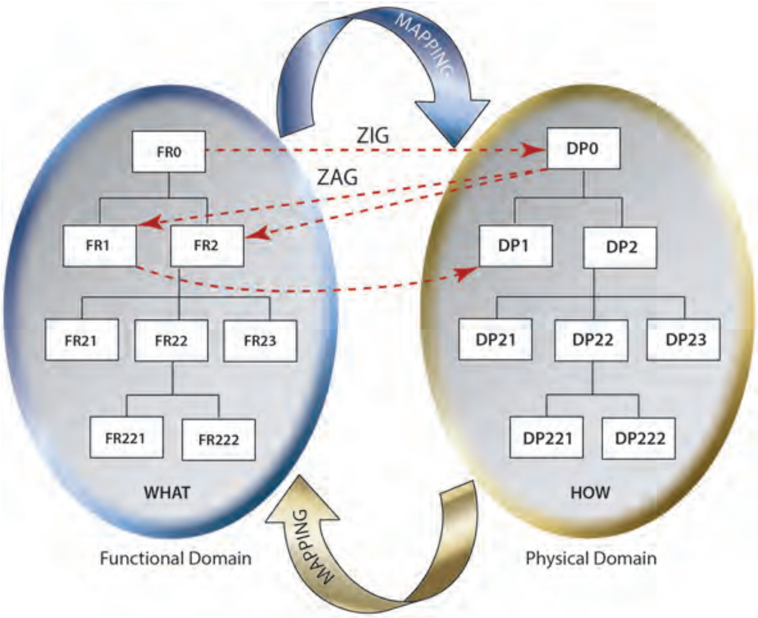


Figure 19: *Zigzagging to decompose FRs and DPs (Ertas and Gulbulak, 2021, [7]).*

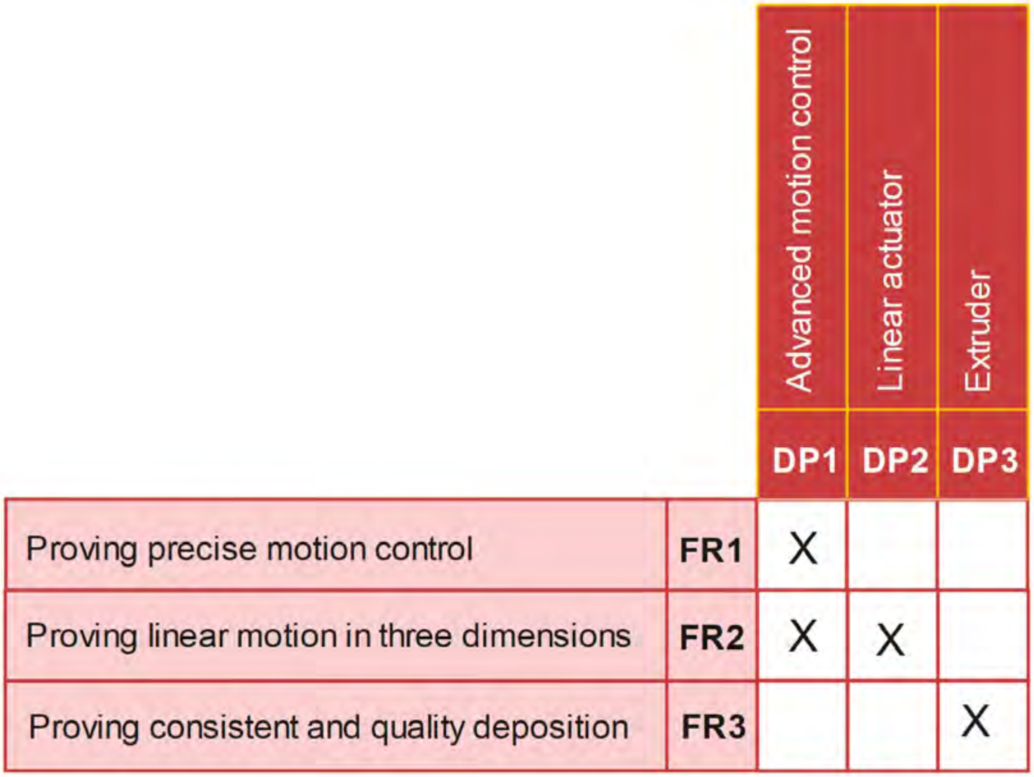
From Figure 5 the high-level functional requirements of the 3D SPM were identified as:

FR1: 3D printer shall be capable of proving precise motion control
FR2: 3D printer shall be capable of proving linear motion in three dimensions
FR3: 3D printer shall be capable of proving consistent and quality deposition

The following design parameters (DPs) are selected to fulfill each of the FRs:

DP 1: Advanced motion control
DP 2: Linear actuator
DP 3: Extruder

Figure 20 summarizes the top-level mapping of FRs to DPs, revealing a de-coupled design as illustrated with the lower triangular matrix and ensuring that the independence axiom is not violated at this stage in the design. As shown in Figures 22, 23, and 24 using zigzagging and maintaining independence axiom the additional FR levels were developed, and satisfying design parameters (3D printing machine components) were identified. Multiple passes were made to ensure an uncoupled or decoupled design at each level. A road map for the levels of decomposition is shown in Figure 21.



		Advanced motion control	Linear actuator	Extruder
		DP1	**DP2**	**DP3**
Proving precise motion control	**FR1**	X		
Proving linear motion in three dimensions	**FR2**	X	X	
Proving consistent and quality deposition	**FR3**			X

Figure 20: *AD high-level design mapping FRs to DPs.*

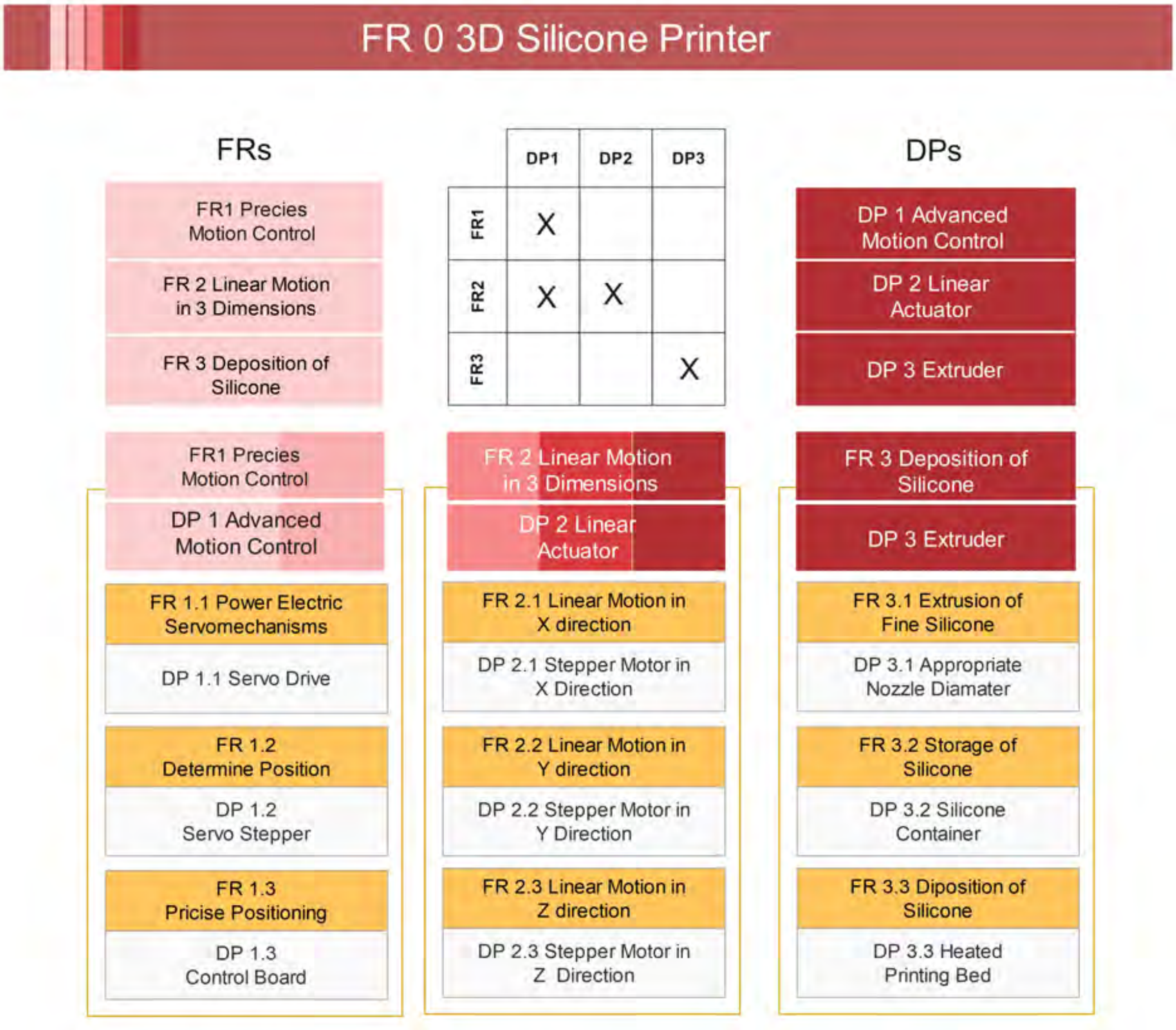
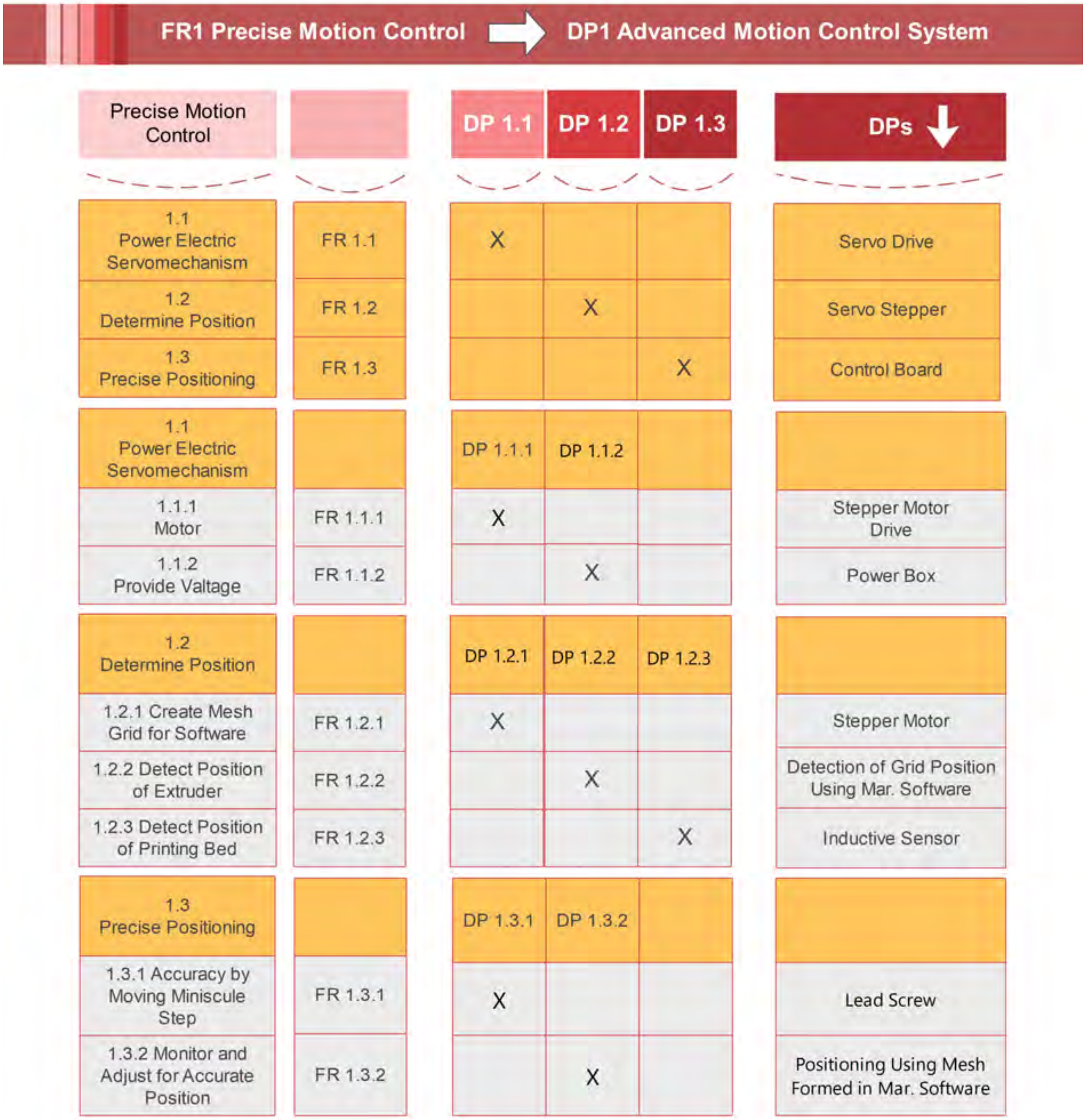


Figure 21: *Rodmap for 3D silicone printing machine component identification.*



FR1 Precise Motion Control ⇒ DP1 Advanced Motion Control System

Precise Motion Control		DP 1.1	DP 1.2	DP 1.3	DPs ↓
1.1 Power Electric Servomechanism	FR 1.1	X			Servo Drive
1.2 Determine Position	FR 1.2		X		Servo Stepper
1.3 Precise Positioning	FR 1.3			X	Control Board
1.1 Power Electric Servomechanism		DP 1.1.1	DP 1.1.2		
1.1.1 Motor	FR 1.1.1	X			Stepper Motor Drive
1.1.2 Provide Valtage	FR 1.1.2		X		Power Box
1.2 Determine Position		DP 1.2.1	DP 1.2.2	DP 1.2.3	
1.2.1 Create Mesh Grid for Software	FR 1.2.1	X			Stepper Motor
1.2.2 Detect Position of Extruder	FR 1.2.2		X		Detection of Grid Position Using Mar. Software
1.2.3 Detect Position of Printing Bed	FR 1.2.3			X	Inductive Sensor
1.3 Precise Positioning		DP 1.3.1	DP 1.3.2		
1.3.1 Accuracy by Moving Miniscule Step	FR 1.3.1	X			Lead Screw
1.3.2 Monitor and Adjust for Accurate Position	FR 1.3.2		X		Positioning Using Mesh Formed in Mar. Software

Figure 22: *Decomposition of FR 1.*

FR 2 Linear Motion in 3 Dimensions → DP 2 Linear Actuators

Linear Motion in 3 dimensions		DP 2.1	DP 2.2	DP 2.3	DPs ↓
2.1 Movement in the x direction	FR 2.1	X			Linear Stepper Motor in the x direction
2.2 Movement in the y direction	FR 2.2		X		Linear Stepper Motor in the y direction
2.3 Movement in the z direction	FR 2.3			X	Linear Stepper Motor in the z direction

2.1 Movement in the x direction		DP 2.1.1	DP 2.1.2	DP 2.1.3	
2.1.1 Motion support in X direction	FR 2.1.1	X			Rod Shaft Guide
2.1.2 Smooth motion limited to X direction	FR 2.1.2		X		Linear Bearings
2.1.3 Motion of extruder in X direction	FR 2.1.3			X	Wheels and Wheel Spacer

2.2 Movement in the y direction		DP 2.2.1	DP 2.2.2	DP 2.2.3	
2.2.1 Motion support in Y direction	FR 2.2.1	X			Rod Shaft Guide
2.2.2 Smooth motion limited to Y direction	FR 2.2.2		X		Linear Bearings
2.2.3 Motion of extruder in Y direction	FR 2.2.3			X	Wheels and Wheel Spacer

2.3 Movement in the z direction		DP 2.3.1	DP 2.3.2		
2.3.1 Motion support for Printing Bed	FR 2.3.1	X			Rod Shaft Guide
2.3.2 Smooth linear and rotation motion for Z rods	FR 2.3.2		X		Ball Bearings

Figure 23: *Decomposition of FR 2.*

FR 3 Deposition of Silicone → DP 3 Extruder

Deposition of Silicone		DP 3.1	DP 3.2	DP 3.3	DPs ↓
3.1 Extrusion of fine Silicone	FR 3.1	X			Appropriate Nozzle Diameter
3.2 Storage of Silicone	FR 3.2		X		Silicone Bottle
3.3 Deposition of Silicone	FR 3.3			X	Heated Printing Bed

3.1 Extrusion of fine Silicone		DP 3.1.1	DP 3.1.2	DP 3.1.3	
3.1.1 Means of movement for silicone from bottle to nozzle	FR 2.1.1	X			Silicone Tubing
3.1.2 Trigger movement of silicone through tubing	FR 2.1.2		X		Peristaltic Pump
3.1.3 Curing of Silicone on Printing Bed	FR 2.1.3			X	UV LED Lights

3.2 Storage of Silicone		DP 3.2.1	
3.2.1 Reservoir of Silicone to attach to printer	FR 3.2.1	X	Novagard Silicone Cartridge

3.3 Deposition of Silicone		DP 3.3.1	DP 3.3.2	DP 3.3.3	DP 3.3.4	DP 3.3.5	DP 3.3.6	
3.3.1 Cooling		X						Blower Fans
3.3.2 Dissipate heat			X					Heat Sink
3.3.3 Control heat				X				Heat Break
3.3.4 Heat silicone					X			Heater Block
3.3.5 Heating Element						X		Heater Cartridge
3.3.6 Sensing heat to adjust temperature							X	Thermistor

Figure 24: *Decomposition of FR 3.*

9 Results and Discussions

The main objective of this paper is to introduce a new TD-integrated tools application to design and develop a 3D silicone printing machine. Parameters in designing and developing 3D printing machines are simplified by considering the main parameters affecting the performance of 3D silicone printing machines. Of course, there are other parameters that could affect performance.

Interpretive Structural Modeling (ISM), a methodology for dealing with complex design and development, is one of the key TD tool components of this research. Building collective intelligence to understand how design parameters affect the performance of 3D SPM and their relationships is an important part of interpretive structural modeling.

Based on the reachability matrix as described in the ISM approach, the digraph shown in Figure 15 for 3D SPM was developed. This figure depicts visually the direct and indirect relationships between the parameters affecting the performance of 3D SPM. As shown in Figure 15, Level V is the most complex one because of its many interactions with the other levels. Three main important parameters, *wear resistance* (measure 5), *operating life* (measure 6), and *linear motion* (measure 8) shown in Figure 15 are the most critical factors which need to be analyzed before other factors as the other factors at the higher level depend on them.

The digraph shown in Figure 15 can be used to measure the complexity of the 3D silicone printing machine using the *Cyclomatic Complexity Measure* [36]. Mathematically, the cyclomatic complexity, M is calculated by

$$M = E - N + 2P \tag{1}$$

where

$E =$ the number of edges of the graph
$N =$ the number of nodes of the graph
$P =$ the number of connected components

The number of edges shown in Figure 15 is 16, the number of nodes is 10, and the number of connected components, P is equal to 1. Then, the cyclomatic complexity M of the digraph given in Figure 15 is

$$M = 16 - 10 + 2 \times 1 = 8$$

The complexity of an issue is difficult to understand when the cyclomatic complexity number is high. The threshold limit value of cyclomatic complexity was suggested by McCabe – "the particular upper bound that has been used for cyclomatic complexity is 10– if the M value is 10 or higher, the issue is said to be complex". We may conclude that the 3D printing machine system represented by Figure 15 is not considered complex, however, it is complicated: it has a high level of difficulty to design.

As shown in Figure 15, the 3D printing machine system contains a hierarchy. Parameters 1 (modular design) and 7 (motion control) are the source elements since they have only outgoing paths. Parameters 9, 10, 4, and 3 represent the linear mapping of the 3D printing machine system. Parameter 2 (weight) affects only parameter 3 (support user activity).

MICMAC chart shown in Figure 16 provides some useful insights into the relative importance and interdependencies among parameters affecting the performance of 3D SPM. In this figure, all performance measures of parameters affecting 3D SPM have been classified into four categories. Cluster I include autonomous factors which they have low driving power and low dependence, hence less importance will be given to them during the design process of 3D SPM. For this case, only one factor *weight* has been identified as an autonomous factor. This indicates that the weight is the least to be considered in the design process of 3D SPM – the factor of weight is disconnected from the 3D SPM system and does not have an influence on other variables–has only one links to *user activity*, measure (3) which may not have a strong effect on the performance.

In Figure 16, Cluster II includes dependent parameters that have low driving power and high dependence. As seen in Figure 16, there are four parameters included in this cluster – *deposition,* measure (9), *surface finish,* measure (10), *dimensional accuracy,* measure (4), and *support user activity,* measure (3). These parameters may not affect other parameters, but they are influenced by other parameters affecting the performance of 3D SPM. In general, parameters (factors) in cluster II considered desired performance objectives. As seen in Figure 15, these factors linearly link each other to satisfy the required objective constraints.

In cluster III, linkage parameters have high driving and high dependence power. Since parameters in cluster III affect each other they are unstable – any change that happens to them will have an effect on others and also feedback on themselves. As seen in Figure 16, there are no unstable parameters in this design.

Cluster IV includes five independent parameters – *modular design,* measure (1), *motion control,* measure (7), *wear resistance,* measure (5), *operating life,* measure (6), and *linear motion,* measure (8) with a strong driving power but very weak dependence. Figure 15 shows that *modular design* and the *motion control* are at the bottom of the digraph having strong driving power – they dictate the performance of the 3D SPM. The performance of the 3D SPM depends on this first step of the design decision – proper modularization of the system and selecting an advanced motion control system.

Applying sequencing (partitioning) in the original DSM shown in Figure 17(b), the feedback marks are reduced to 3. as shown in Figure 25(a), the cluster loop of coupled parameters of 5, 6, and 8 cycles (requires iteration) is the most complex and tedious part of this project.

Two types of other sub-couplings also exist within this cluster loop. (a) coupling between 5 and 8, and (b) coupling between parameters 6 and 8. Many iterations may be required to conclude and decide on the values of parameters of 3D SPM after an initial assumption about one of them is made.

9.1 Tearing

Tearing is the process of reordering coupled tasks within a block to find an initial ordering to start the iteration process [37]. Once coupled tasks are identified in a DSM, they are subjected to the next level of analysis – that is DSM tearing: finding some of the feedback marks which have the minimum impact on the product design that can be deleted from the matrix. Although tearing may help to decrease the complexity and size of the cluster and speed up the design process, the disadvantage is a loss of information. That is why the number of tears should be carefully kept to a reasonable number to prevent depending on too much on initial guesses.

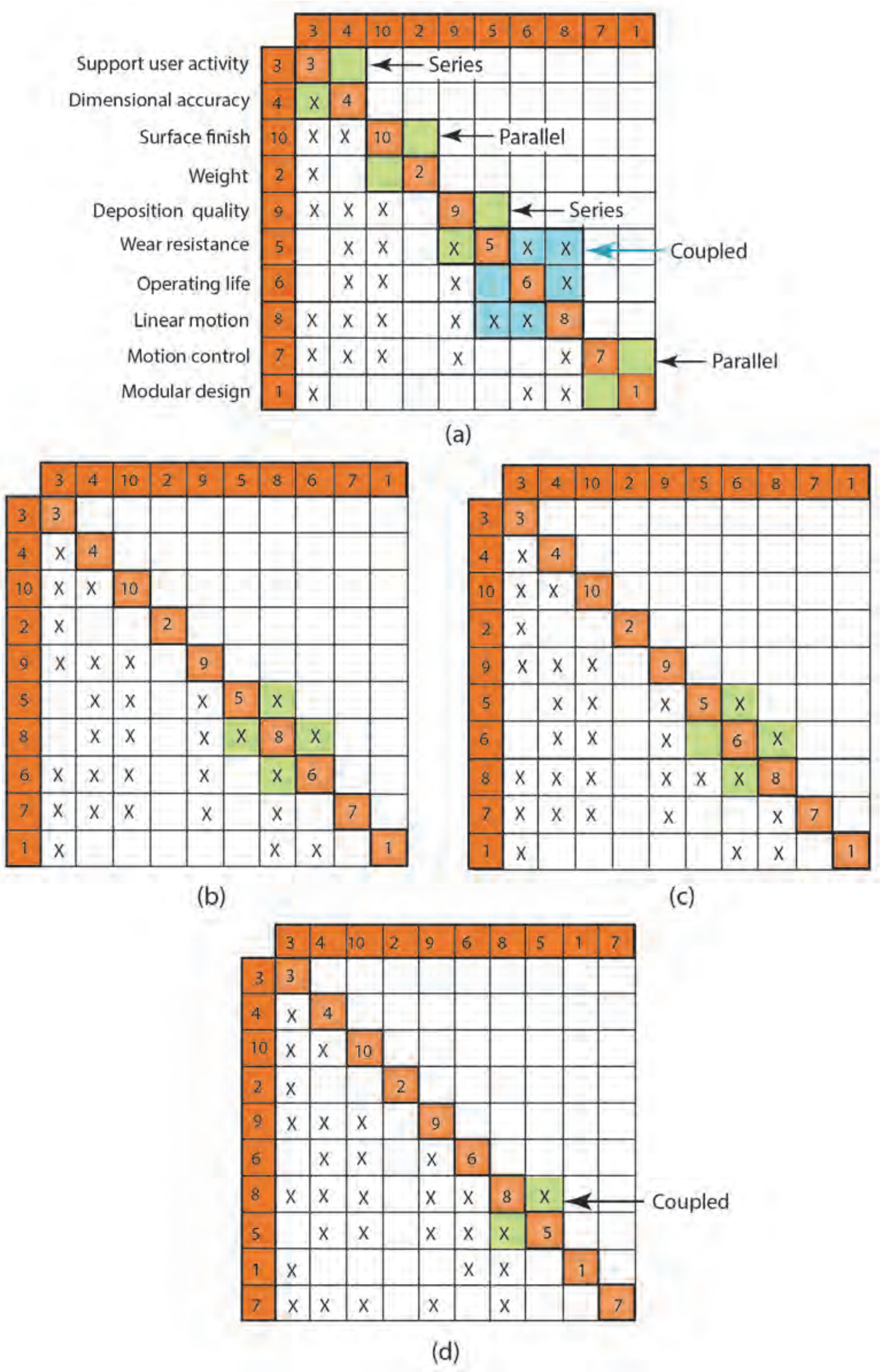
Three cases of tearing are shown in Figure 24 (b), (c), and (d).

Tearing-Case (b): Tearing the feedback mark ("X" mark) at the intersection of parameters column-6 and row-5) will be eliminated from the matrix shown in Figure 25 (a) to reduce the complexity and size of the cluster. Figure 25 (b) shows the partitioned matrix after tearing. As seen from this figure, the complexity and size of the cluster reduced considerably compared with Figure 25 (a). The resulting DSM has now two couplings: (a) parameters 5 and 8, and (b) parameters (8) and (6).

Tearing-Case (c): Tearing the feedback mark ("X" mark) at the intersection of parameters column-8 and row-5) will be eliminated from the matrix shown in Figure 25 (a) to reduce the complexity and size of the cluster. As shown in Figure 25 (c), the resulting DSM matrix has reduced to one series parameter activity (parameters 5 and 6) and one couple (parameters 6 and 8). Compared with Figure 25 (b) this is also an improved situation.

Tearing-Case (d): In this case, tearing the feedback mark ("X" mark) at the intersection of parameters column-8 and row-6) will be eliminated from the matrix shown in Figure 25 (a)). As seen in Figure 24 (d), tearing resulted in only one coupling between parameters 8 and 5.

In summary, the torn DSM shown in Figure 25 (d) provides a more complete and less complex parameter modeling framework as compared to others. With this new DSM, the relationship between 3D



		3	4	10	2	9	5	6	8	7	1
Support user activity	3	3									
Dimensional accuracy	4	X	4								
Surface finish	10	X	X	10							
Weight	2	X			2						
Deposition quality	9	X	X	X		9					
Wear resistance	5		X	X		X	5	X	X		
Operating life	6		X	X		X		6	X		
Linear motion	8	X	X	X		X	X	X	8		
Motion control	7	X	X	X		X			X	7	
Modular design	1	X						X	X		1

(a)

	3	4	10	2	9	5	8	6	7	1
3	3									
4	X	4								
10	X	X	10							
2	X			2						
9	X	X	X		9					
5		X	X		X	5	X			
8		X	X		X	X	8	X		
6	X	X	X		X		X	6		
7	X	X	X		X		X		7	
1	X						X	X		1

(b)

	3	4	10	2	9	5	6	8	7	1
3	3									
4	X	4								
10	X	X	10							
2	X			2						
9	X	X	X		9					
5		X	X		X	5	X			
6		X	X		X		6	X		
8	X	X	X		X	X	X	8		
7	X	X	X		X			X	7	
1	X						X	X		1

(c)

	3	4	10	2	9	6	8	5	1	7
3	3									
4	X	4								
10	X	X	10							
2	X			2						
9	X	X	X		9					
6		X	X		X	6				
8	X	X	X		X	X	8	X		
5		X	X		X	X	X	5		
1	X					X	X		1	
7	X	X	X		X		X			7

(d)

Figure 25: *Partitioning of Figure 17(b).*

SPM parameters can be effectively identified. Besides one coupling, the rest of the relationships between parameters are either sequential or parallel which reduces the complexity of the system considerably.

Analyzing sequencing results, the "X" marks below the diagonal represent a precedence relationship between parameters. As mentioned earlier, the row node requires input in the form of information from the column node. For example, by tracing across the row of the matrix, to determine the required dimensional accuracy (parameter 4), the 3D SPM designer must know the user's/customer's (parameter 3) requirement. Determining the surface finish quality (parameter 10) requires dimensional accuracy information.

As shown in Figure 25 (d), the re-ordering is achieved by using partitioning for an optimum sequence of parameter decisions for the design and development of 3D SPM. This parameter-based DSM provides a structural map of the design processes of 3D SPM. As seen from the figure, the *top-down* design process begins with prior knowledge, experiences, and expectations provided by users. Depending on the application this information will establish the *dimensional accuracy* required by the 3D SPM. Dimensional accuracy will be input to *surface finish* which dictates the *deposition quality.* After the operating life assumption of the machine is decided, iterative decision-making between coupled parameters *wear* and *linear motion* will be completed. To minimize the cost of repair, allow easy upgrades, and reduce the 3D printer weight *modular design* will be developed. Parameter *motion control* receives the most input from the other parameters and will be selected carefully to control the dynamics of the motion of the 3D SPM.

"Parameter-based DSMs are truly integrative applications and a combinational use of top-down and bottom-up techniques in process modeling may reveal valuable insights into the process structure [38]."

9.2 Banding

DSM banding is an alternative to DSM partitioning to identify the sets of independent (i.e. parallel or concurrent) elements [39]. It is similar to partitioning the DSM using the Reachability Matrix Method without considering the feedback marks (a band corresponds to a level) [40]. Bands represent the critical path to the project, where one element in each band is a potential bottleneck [41].

As shown in Figure 26, there are seven bands in the partitioned matrix. Bands (including certain parameters) are independent and do not depend on each other for information. For example, parameters 10 and 2 do not depend on each other for information. Therefore, they belong to the same band and both parameter values can be decided independently (parallel). Similarly, parameters 5, 1, and 7 do not depend on each other for information. Therefore, they belong to the same band.

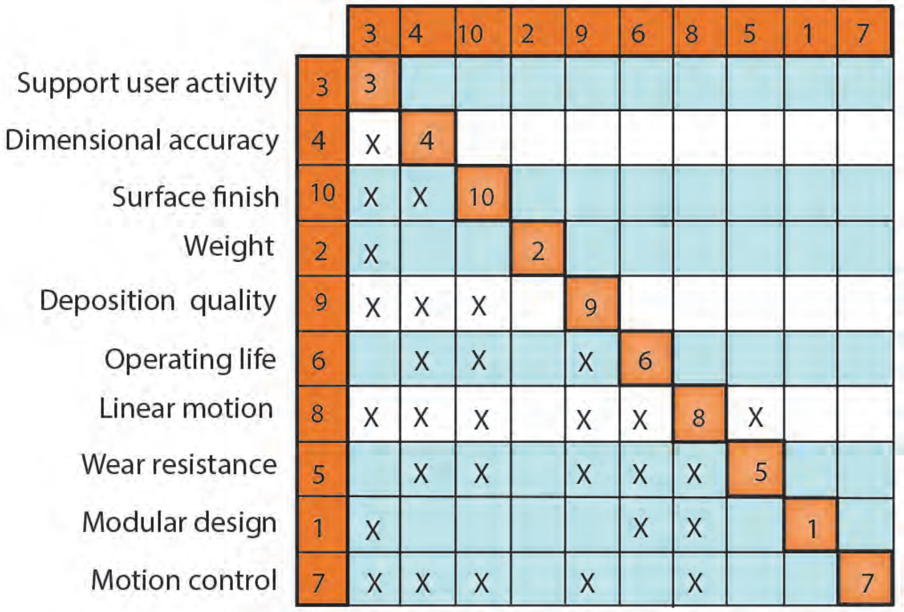
We used banding to visually show the system parameters that do not affect one another. This is important information in that designers can disregard areas where they might have previously wasted time considering interfaces. Banding may prove to be a good tool to test components/parameters in parallel, resulting in significant time and cost savings for test phases. [42].

9.3 Modular Design

The main idea of the 3D SPM modular design strategy was to develop loosely coupled modules, where modules can be decoupled, separated, modified, and replaced. Using TD-integrated tools, we have successfully designed and built functional 3D SPM as shown in Figure 27. We have developed 10 modules considering scalability and new features that can be added to the 3D SPM without redesigning the whole system again. Exploded modeling of modules and their components are shown in Appendix B.

10 Conclusions and Future Study

In this paper, we covered the integration of well-known TD tools that have been applied in many fields including product development, project management, many engineering disciplines, design of the organization, sustainable development, social issues, environmental issues, and others across many industries including automotive, aerospace, telecom, semiconductor, defense, transportation, energy, healthcare, agriculture, and more.



		3	4	10	2	9	6	8	5	1	7
Support user activity	3	3									
Dimensional accuracy	4	X	4								
Surface finish	10	X	X	10							
Weight	2	X			2						
Deposition quality	9	X	X	X		9					
Operating life	6		X	X		X	6				
Linear motion	8	X	X	X		X	X	8	X		
Wear resistance	5		X	X		X	X	X	5		
Modular design	1	X					X	X		1	
Motion control	7	X	X	X		X		X			7

Figure 26: *Banded DSM after partitioned.*

Figure 27: *3D SPM final product.*

This TD- integrated design tools approach for the design of 3D SPM using Kano, HOQ/QFD, TRIZ, AD, ISM, and DSM Tools, as shown in Figure 1, was useful in identifying an applicable set of requirements for the 3D SPM through the use of the Kano Survey; identified and addressed conflicts via HOQ; enabled innovative design through the use of HOQ and TRIZ; facilitated the decoupled design through AD; informed the focus areas of design and implementation through the use of ISM and DSM.

Through this research, we have provided the application of TD-integrated design tools to 3D SPM design and successfully built the 3D printing machine. The novel approach proposed in this paper can also be utilized by engineers and researchers for other applications such as product development, making decisions on complex societal issues, planning and strategy development, etc. Many examples of each individual tool mentioned in this paper and their application to analysis techniques are covered in the open literature. However, the application of the TD-integrated design tools methodology discussed in this paper is limited at this time.

The use of TD-integrated design tools increases our knowledge and understanding of approaches to analyzing parameter dependencies in 3D SPM systems and thereby facilitates the reduction of uncertainty in product development.

The value of the parameters affecting the performance of 3D SPM will be selected after initial experiments which will be the second part of this paper. Usually, the values of parameters are not determined independently since it is an issue of interaction among the design parameters of 3D SPM.

Future works will include the following four aspects: (1) Extensive experimentation to identify the tuning parameters of 3D SPM and investigating their degree of effects on the performance of 3D SPM using the Taguchi-ANOVA method, (2) Investigation of the parameters affecting the curing of challenging material of liquid silicone for the proposed 3D SPM in this paper, (3) Finalizing the detail design and exploring the production-capable 3D SPM for faster reliable printing, (4) Designing of smart 3D printers communicate with each other to share the large-scale of printing work simultaneously to reduce the cost and time for production through Digital Engineering (DE).

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Dr. A. Ertas, Professor of Mechanical Engineering and director of the Academy for Transdisciplinary Studies at Texas Tech University, received his master's and Ph.D. from Texas A&M University. He had 12 years of industrial experience prior to pursuing graduate studies. Dr. A. Ertas has been the driving force behind the conception and development of the transdisciplinary model for education and research. His pioneering efforts in transdisciplinary research and education have been recognized internationally by several awards. He was a Senior Research Fellow of the ICC Institute at the University of Texas Austin (1996-2019), a Fellow of ASME, a Fellow of Society for Design and Process Science (SDPS), Founding Fellow of Luminary Research Institute in Taiwan, an honorary member of International Center for Transdisciplinary Research (CIRET), France, and a member of ASEE. Dr. Ertas has earned both national and international reputations in engineering design. Dr. Ertas is the author of a number of books, among them: Ertas, A. and Jones, J. C., *The Engineering Design Process,* John Wiley & Sons, Inc., first edition 1993 and second edition 1996; Ertas, A., *Prevention through Design (PtD): Transdisciplinary Process,* funded by the National Institute for Occupational Safety and Health, 2010; Ertas, A., *Engineering Mechanics and Design Applications, Transdisciplinary Engineering Fundamentals*, CRC Press, Taylor & Francis Group, 2011; A. Ertas, A., *Transdisciplinarity Engineering Design Process,* John Wiley & Sons, 2018. He has edited many research books specific to transdisciplinary engineering design, among them: Ertas, A., (editor), *Transdisciplinarity: Bridging Natural Science, Social Science, Humanities & Engineering*, ATLAS Publications, 2011; B. Nicolescu, B. and Ertas A., (editors), *Transdisciplinary Theory and Practice*, ATLAS Publications, 2013; Nicolescu, B., Ertas, A., (Editors), *Transdisciplinary Education, Philosophy, & Applications,* ATLAS Publications, 2014; Ertas, A., Nicolescu, B., S. Gehlert, S., (Editors), *Convergence: Transdisciplinary Knowledge & Approaches to Education and Public Health*, ATLAS Publishing, 2016; Nicolescu, B., Yeh, R. T., Ertas, A., (Editors), *Being Transdisciplinary.* ATLAS Publishing, 2019; Ertas, A., (Editor), *Additive Manufacturing Research & Applications*, MDPI Publishing, Switzerland. He has also edited/co-edited more than 35 conference proceedings. Dr. Ertas' contributions to teaching and research have been recognized by numerous honors and awards. He has published over 200 scientific papers and book chapters that cover many engineering technical fields. He has been PI or Co-PI on over 40 funded research projects. Under his supervision, more than 190 MS and Ph.D. graduate students have received degrees.

Appendix A

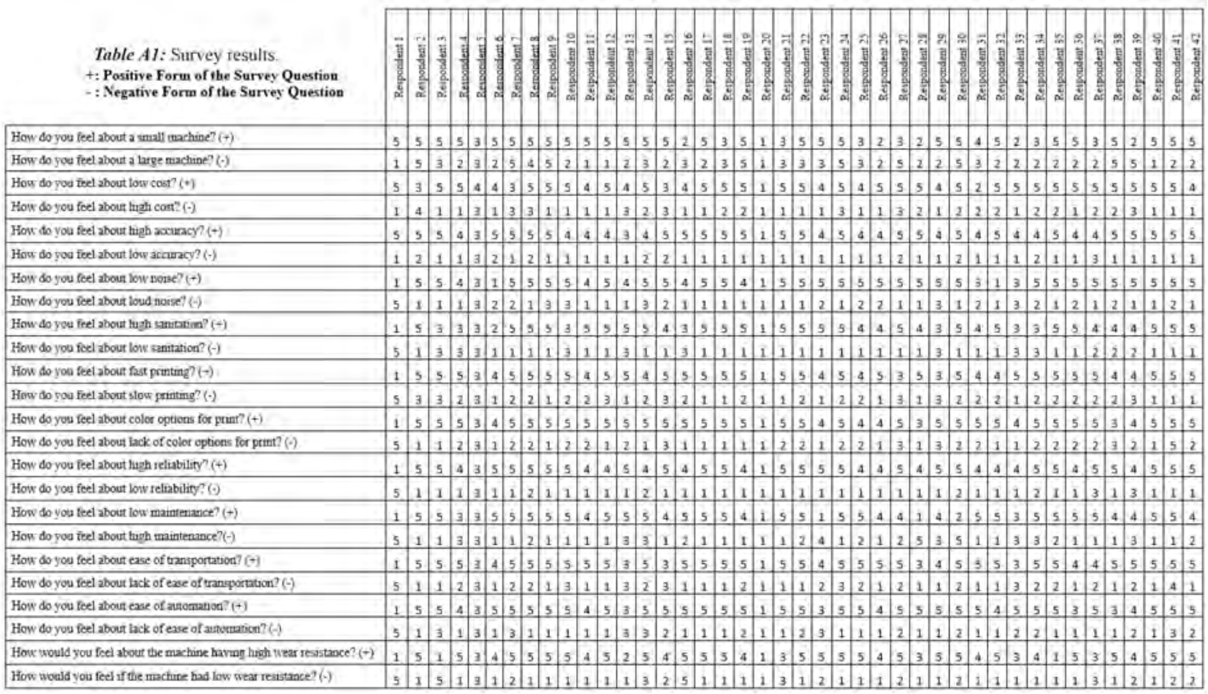


Table A1: Survey results.

+: Positive Form of the Survey Question
- : Negative Form of the Survey Question

	Respondent 1	Respondent 2	Respondent 3	Respondent 4	Respondent 5	Respondent 6	Respondent 7	Respondent 8	Respondent 9	Respondent 10	Respondent 11	Respondent 12	Respondent 13	Respondent 14	Respondent 15	Respondent 16	Respondent 17	Respondent 18	Respondent 19	Respondent 20	Respondent 21
How do you feel about a small machine? (+)	5	5	5	5	3	5	5	5	5	5	5	5	5	5	5	2	5	3	5	1	3
How do you feel about a large machine? (-)	1	5	3	2	3	2	5	4	5	2	1	1	2	3	2	3	2	3	5	1	3
How do you feel about low cost? (+)	5	3	5	5	4	4	3	5	5	5	4	5	4	5	3	4	5	5	5	1	5
How do you feel about high cost? (-)	1	4	1	1	3	1	3	3	1	1	1	1	3	2	3	1	1	2	2	1	1
How do you feel about high accuracy? (+)	5	5	5	4	3	5	5	5	5	4	4	4	3	4	5	5	5	5	5	1	5
How do you feel about low accuracy? (-)	1	2	1	1	3	2	1	2	1	1	1	1	1	2	2	1	1	1	1	1	1
How do you feel about low noise? (+)	1	5	5	4	3	1	5	5	5	5	4	5	4	5	5	4	5	5	4	1	5
How do you feel about loud noise? (-)	5	1	1	1	3	2	2	1	3	3	1	1	1	3	2	1	1	1	1	1	1
How do you feel about high sanitation? (+)	1	5	3	3	3	2	5	5	5	3	5	5	5	5	4	3	5	5	5	1	5
How do you feel about low sanitation? (-)	5	1	3	3	3	1	1	1	1	3	1	1	3	1	1	3	1	1	1	1	1
How do you feel about fast printing? (+)	1	5	5	5	3	4	5	5	5	5	4	5	5	4	5	5	5	5	5	1	5
How do you feel about slow printing? (-)	5	3	3	2	3	1	2	2	1	2	2	3	1	2	3	2	1	1	2	1	1
How do you feel about color options for print? (+)	1	5	5	5	3	4	5	5	5	5	5	5	5	5	5	5	5	5	5	1	5
How do you feel about lack of color options for print? (-)	5	1	1	2	3	1	2	2	1	2	2	1	2	1	3	1	1	1	1	1	2
How do you feel about high reliability? (+)	1	5	5	4	3	5	5	5	5	5	4	4	5	4	5	4	5	5	4	1	5
How do you feel about low reliability? (-)	5	1	1	1	3	1	1	2	1	1	1	1	1	2	1	1	1	1	1	1	1
How do you feel about low maintenance? (+)	1	5	5	3	3	5	5	5	5	5	4	5	5	5	4	5	5	5	4	1	5
How do you feel about high maintenance?(-)	5	1	1	3	3	1	1	2	1	1	1	1	3	3	1	2	1	1	1	1	1
How do you feel about ease of transportation? (+)	1	5	5	5	3	4	5	5	5	5	5	5	3	5	3	5	5	5	5	1	5
How do you feel about lack of ease of transportation? (-)	5	1	1	2	3	1	2	2	1	3	1	1	3	2	3	1	1	1	2	1	1
How do you feel about ease of automation? (+)	1	5	5	4	3	5	5	5	5	5	4	5	3	5	5	5	5	5	5	1	5
How do you feel about lack of ease of automation? (-)	5	1	3	1	3	1	3	1	1	1	1	1	3	3	2	1	1	1	2	1	1
How would you feel about the machine having high wear resistance? (+)	1	5	1	5	3	4	5	5	5	5	4	5	2	5	4	5	5	5	4	1	3
How would you feel if the machine had low wear resistance? (-)	5	1	5	1	3	1	2	1	1	1	1	1	1	3	2	5	1	1	1	1	3

	Respondent 22	Respondent 23	Respondent 24	Respondent 25	Respondent 26	Respondent 27	Respondent 28	Respondent 29	Respondent 30	Respondent 31	Respondent 32	Respondent 33	Respondent 34	Respondent 35	Respondent 36	Respondent 37	Respondent 38	Respondent 39	Respondent 40	Respondent 41	Respondent 42
How do you feel about a small machine? (+)	5	5	5	3	2	3	2	5	5	4	5	2	3	5	5	3	5	2	5	5	5
How do you feel about a large machine? (-)	3	3	5	3	2	5	2	2	5	3	2	2	2	2	2	2	5	5	1	2	2
How do you feel about low cost? (+)	5	4	5	4	5	5	5	4	5	2	5	5	5	5	5	5	5	5	5	5	4
How do you feel about high cost? (-)	1	1	3	1	1	3	2	1	2	2	2	1	2	2	1	2	2	3	1	1	1
How do you feel about high accuracy? (+)	5	4	5	4	4	5	5	4	5	4	5	4	4	5	4	4	5	5	5	5	5
How do you feel about low accuracy? (-)	1	1	1	1	1	2	1	1	2	1	1	1	2	1	1	3	1	1	1	1	1
How do you feel about low noise? (+)	5	5	5	5	5	5	5	5	5	3	1	3	5	5	5	5	5	5	5	5	5
How do you feel about loud noise? (-)	1	2	1	2	2	1	1	3	1	2	1	3	2	1	2	1	2	1	1	2	1
How do you feel about high sanitation? (+)	5	5	5	4	4	5	4	3	5	4	5	3	3	5	5	4	4	4	5	5	5
How do you feel about low sanitation? (-)	1	1	1	1	1	1	1	3	1	1	1	3	3	1	1	2	2	2	1	1	1
How do you feel about fast printing? (+)	5	4	5	4	5	3	5	3	5	4	4	5	5	5	5	5	4	4	5	5	5
How do you feel about slow printing? (-)	2	1	2	2	1	3	1	3	2	2	2	1	2	2	2	2	2	3	1	1	1
How do you feel about color options for print? (+)	5	4	5	4	4	5	3	5	5	5	5	4	5	5	5	5	3	4	5	5	5
How do you feel about lack of color options for print? (-)	2	1	2	2	1	3	1	3	2	2	1	1	2	2	2	2	3	2	1	5	2
How do you feel about high reliability? (+)	5	5	5	4	4	5	4	5	5	4	4	4	5	5	4	5	5	4	5	5	5
How do you feel about low reliability? (-)	1	1	1	1	1	1	1	1	2	1	1	1	2	1	1	3	1	3	1	1	1
How do you feel about low maintenance? (+)	5	1	5	5	4	4	1	4	2	5	5	3	5	5	5	5	4	4	5	5	4
How do you feel about high maintenance?(-)	2	4	1	2	1	2	5	3	5	1	1	3	3	2	1	1	1	3	1	1	2
How do you feel about ease of transportation? (+)	5	4	5	5	5	5	3	4	5	5	5	3	5	5	4	4	5	5	5	5	5
How do you feel about lack of ease of transportation? (-)	1	2	3	2	1	2	1	1	2	1	1	3	2	2	1	2	1	2	1	4	1
How do you feel about ease of automation? (+)	5	3	5	5	4	5	5	5	5	5	4	5	5	5	3	5	3	4	5	5	5
How do you feel about lack of ease of automation? (-)	2	3	1	1	1	2	1	1	2	1	1	2	2	1	1	1	1	2	1	3	2
How would you feel about the machine having high wear resistance? (+)	5	5	5	5	4	5	3	5	5	4	5	3	4	1	5	3	5	4	5	5	5
How would you feel if the machine had low wear resistance? (-)	1	2	1	1	1	2	1	1	2	1	1	1	1	1	1	3	1	2	1	2	2

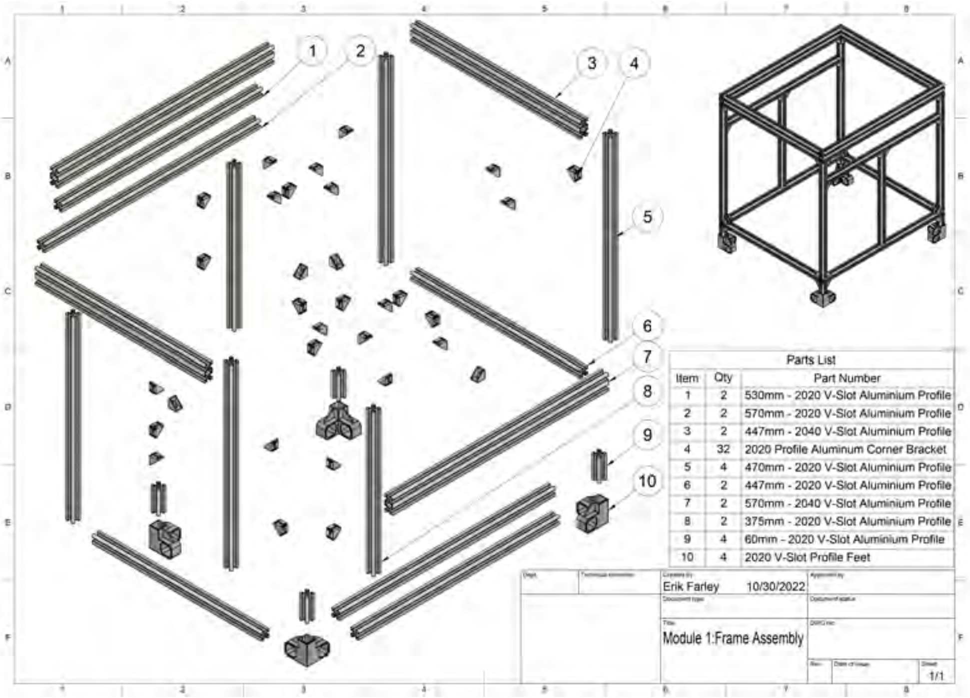
Table A2: TRIZ Contradiction Matrix (Engineering Characteristics).

Worsening Feature ➡ Improving Feature ⬇		Reliability 27	Accuracy of measurement 28	Accuracy of manufacturing 29	Harmful factor acting on object 30	Harmful side-effects 31	Manufacturibility 32	Convenience of use 33	Repairability 34	Adaptability 35	Complexity of system/device 36	Complexity of control 37	Level of automation 38	Productivity 39
21	Power	19,24 26,31	32,15 2	32,2	19,22 31,2	2,35 18	26,10 34	26,35 18	35,2 10,34	19,17 34	20,19 30,34	19,35 16	28,2 17	28,35 34
22	Waste of energy	11,10 35	32		21,22 35,2	21,35 2,22		35,32 1	2,19		7,23	35,3 15,23	2	28,10 29,35
23	Waste of substance	10,29 39,35	16,34 31,28	35,10 24,31	33,22 30,40	10,1 34,29	15,34 33	32,28 2,24	2,35 34,27	15,10 2	35,10 28,24	35,18 10,13	35,10 18	28,35 10,23
24	Loss of information	10,28 23			22,10 1	10,21 22	32	27,22				35,33	35	13,23 15
25	Waste of time	10,30 4	24,34 28,32	24,26 28,18	35,18 34	35,22 18,39	35,28 34,4	4,28 10,34	32,1 10	35,28	6,29	18,28 32,10	24,28 35,30	
26	Amount of substance	18,3 28,40	13,2 28	33,30	35,33 29,31	3,35 40,39	29,1 35,27	35,29 25,10	2,32 10,25	15,3 29	3,13 27,10	3,27 29,18	8,35	13,29 3,27
27	Reliability		32,3 11,23	11,32 1	27,35 2,40	35,2 40,26		27,17 40	1,11	13,25 8,24	13,35 1	27,40 28	11,13 27	1,35 29,38
28	Accuracy of measurement	5,11 1,23			28,24 22,26	3,33 39,10	6,35 25,18	1,13 17,34	1,32 13,11	13,35 2	27,35 10,34	26,24 32,28	28,2 10,34	10,34 28,32
29	Accuracy of manufacturing	11,32 1			26,28 10,36	4,17 34,26		1,32 35,23	25,10		26,2 18		26,28 18,23	10,18 32,39
30	Harmful factors acting on object	27,24 2,40	28,33 23,26	26,28 10,18			24,35 2	2,25 28,39	35,10 2	35,11 22,31	22,19 29,40	22,19 29,40	33,3 34	22,35 13,24
31	Harmful side-effects	24,2 40,39	3,33 26	4,17 34,26							19,1 31	2,21 27,1	2	22,35 18,39
32	Manufacturability		1,35 12,18		24,2			2,5 13,16	35,1 11,9	2,13 15	27,26 1	6,28 11,1	8,28 1	35,1 10,28
33	Convenience of use	17,27 8,40	25,13 2,34	1,32 35,23	2,25 28,39		2,5 12		12,26 1,32	15,34 1,16	32,26 12,17		1,34 12,3	15,1 28
34	Repairability	11,10 1,16	10,2 13	25,10	35,10 2,16		1,35 11,10	1,12 26,15		7,1 4,16	35,1 13,11		34,35 7,13	1,32 10
35	Adaptability	35,13 8,24	35,5 1,10		35,11 32,31		1,13 31	15,34 1,16	1,16 7,4		15,29 37,28	1	27,34 35	35,28 6,37
36	Complexity of system/device	13,35 1	2,26 10,34	26,24 32	22,19 29,40	19,1	27,26 1,13	27,9 26,24	1,13	29,15 28,37		15,10 37,28	15,1 24	12,17 28
37	Complexity of control	27,40 28,8	26,24 32,38		22,19 29,28	2,21	5,28 11,29	2,5	12,26	1,15	15,10 37,28		34,21	35,18
38	Level of automation	11,27 32	28,26 10,34	28,26 18,23	2,33	2	1,26 13	1,12 34,3	1,35 13	27,4 1,35	15,24 10	34,27 25		5,12 35,26
39	Productivity	1,35 10,38	1,10 34,28	18,10 32,1	22,35 13,24	35,22 18,39	35,28 2,24	1,28 7,10	1,32 10,25	1,35 28,37	12,17 28,24	35,18 27,2	5,12 27,2	

Table A3: TRIZ–40 Principles.

Principles	**Principles**
1. Segmentation	21. Rushing through
2. Extraction (taking out)	22. Convert harm into benefit
3. Local Quality	23. Feedback
4. Asymmetry	24. Mediator (intermediary)
5. Combination (merging)	25. Self-service
6. Universality	26. Copying
7. Nesting	27. Inexpensive short life
8. Counterweight (anti-weight)	28. Replacement of a mechanical system
9. Prior Counteraction	29. Use pneumatic or hydraulic systems
10. Prior Action	30. Flexible film or thin membranes
11. Cushion in Advance	31. Use of porous materials
12. Equipotentiality	32. Changing the colour
13. Inversion (the other way round)	33. Homogeneity
14. Spheroidality- Curvature	34. Rejecting and regenerating parts
15. Dynamicity	35. Parameter Change
16. Partial, overdone or excessive action	36. Phase transition
17. Moving to a new dimension	37. Thermal expansion
18. Mechanical vibration	38. Use strong oxidisers
19. Periodic action	39. Inert environment
20. Continuity of useful action	40. Composite materials

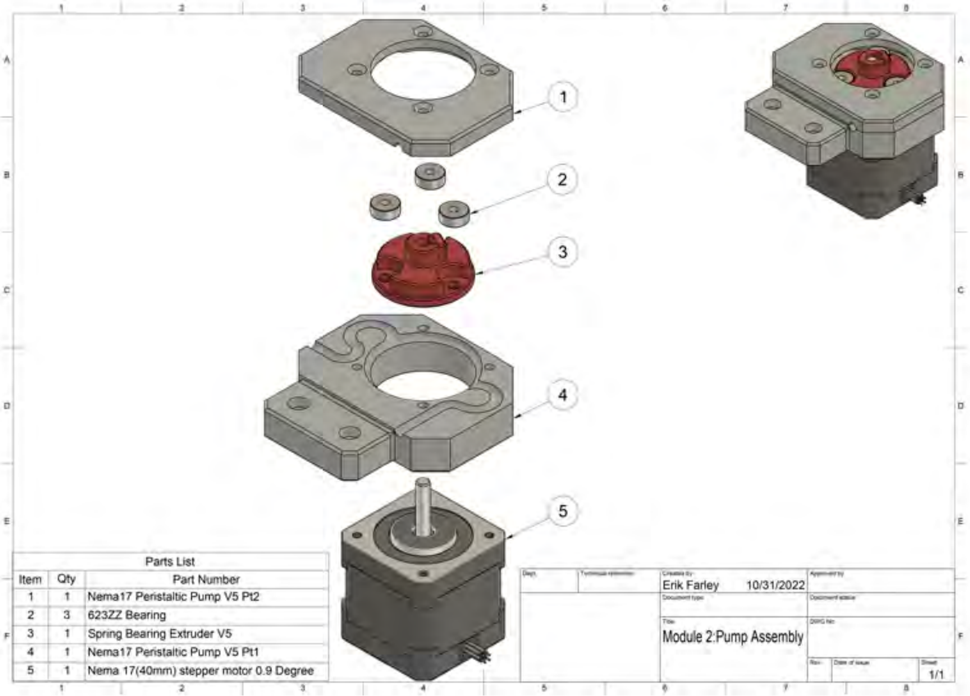
Source of Table 3.8: Altshuller G. 40 Principles: TRIZ Keys to Technical Innovation. Technical Innovation Center; 2001.



Parts List

Item	Qty	Part Number
1	2	530mm - 2020 V-Slot Aluminium Profile
2	2	570mm - 2020 V-Slot Aluminium Profile
3	2	447mm - 2040 V-Slot Aluminium Profile
4	32	2020 Profile Aluminum Corner Bracket
5	4	470mm - 2020 V-Slot Aluminium Profile
6	2	447mm - 2020 V-Slot Aluminium Profile
7	2	570mm - 2040 V-Slot Aluminium Profile
8	2	375mm - 2020 V-Slot Aluminium Profile
9	4	60mm - 2020 V-Slot Aluminium Profile
10	4	2020 V-Slot Profile Feet

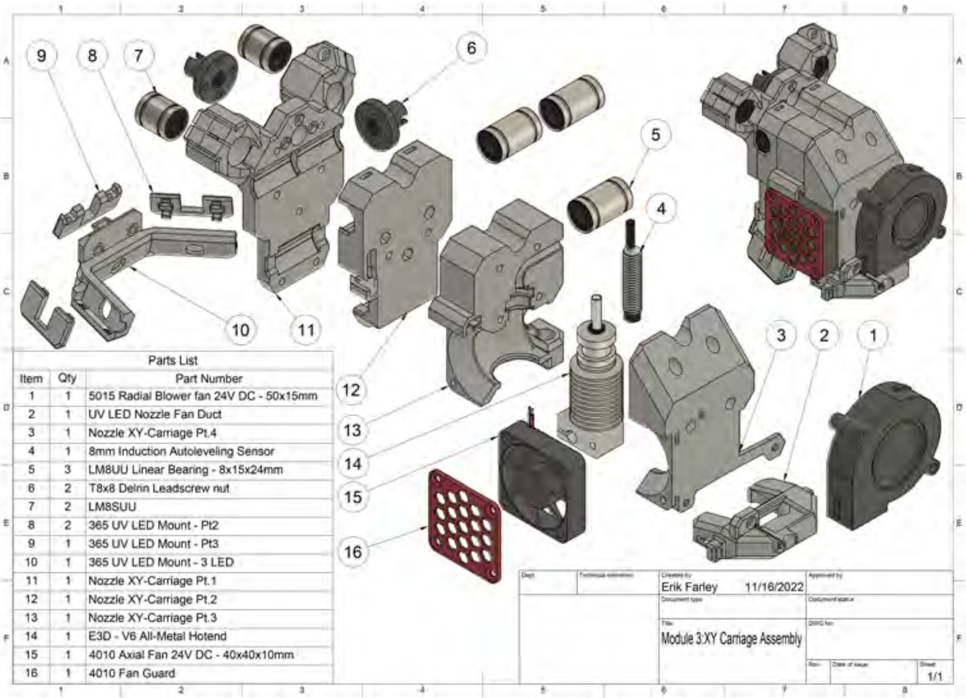
Figure B1: Module 1: Frame assembly.



Parts List

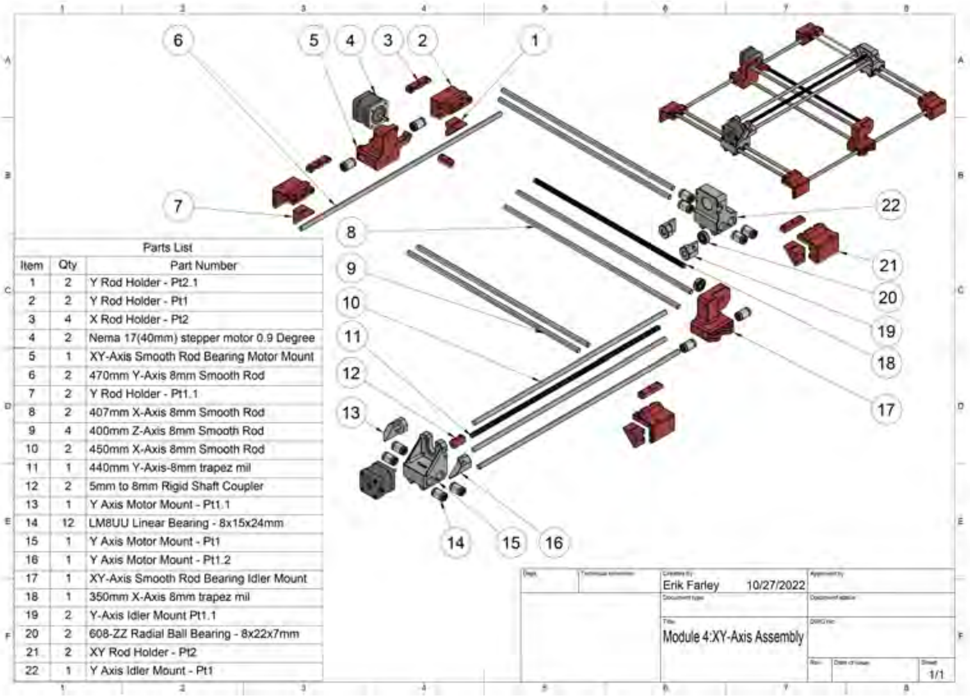
Item	Qty	Part Number
1	1	Nema17 Peristaltic Pump V5 Pt2
2	3	623ZZ Bearing
3	1	Spring Bearing Extruder V5
4	1	Nema17 Peristaltic Pump V5 Pt1
5	1	Nema 17(40mm) stepper motor 0.9 Degree

Figure B2: Module 2: Pump assembly.



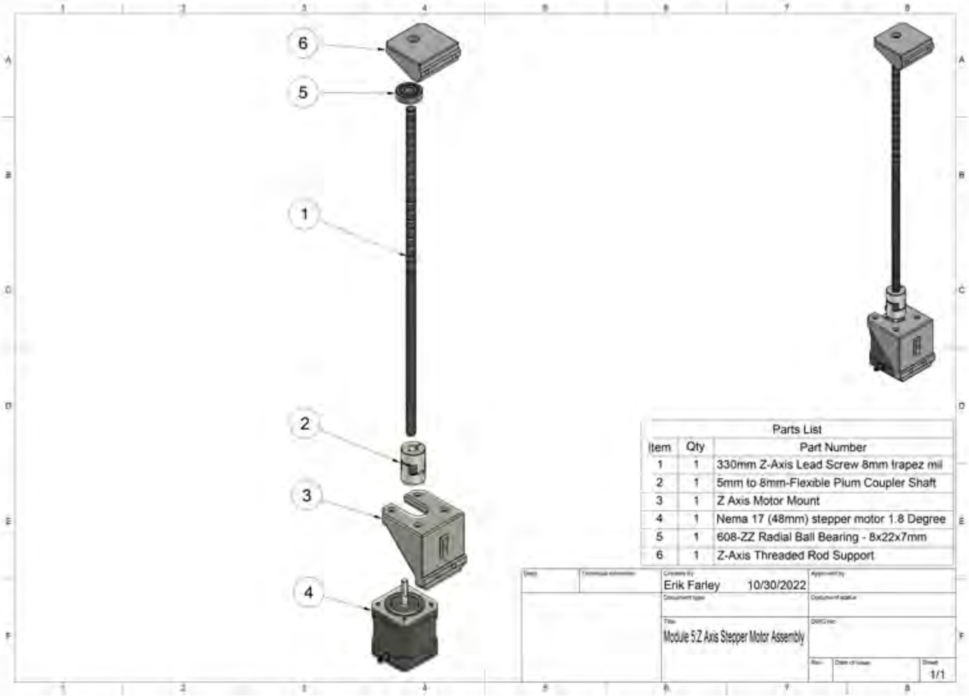
Parts List		
Item	Qty	Part Number
1	1	5015 Radial Blower fan 24V DC - 50x15mm
2	1	UV LED Nozzle Fan Duct
3	1	Nozzle XY-Carriage Pt.4
4	1	8mm Induction Autoleveling Sensor
5	3	LM8UU Linear Bearing - 8x15x24mm
6	2	T8x8 Delrin Leadscrew nut
7	2	LM8SUU
8	2	365 UV LED Mount - Pt2
9	1	365 UV LED Mount - Pt3
10	1	365 UV LED Mount - 3 LED
11	1	Nozzle XY-Carriage Pt.1
12	1	Nozzle XY-Carriage Pt.2
13	1	Nozzle XY-Carriage Pt.3
14	1	E3D - V6 All-Metal Hotend
15	1	4010 Axial Fan 24V DC - 40x40x10mm
16	1	4010 Fan Guard

Figure B3: Module 3: XY Carriage assembly.



Parts List		
Item	Qty	Part Number
1	2	Y Rod Holder - Pt2.1
2	2	Y Rod Holder - Pt1
3	4	X Rod Holder - Pt2
4	2	Nema 17(40mm) stepper motor 0.9 Degree
5	1	XY-Axis Smooth Rod Bearing Motor Mount
6	2	470mm Y-Axis 8mm Smooth Rod
7	2	Y Rod Holder - Pt1.1
8	2	407mm X-Axis 8mm Smooth Rod
9	4	400mm Z-Axis 8mm Smooth Rod
10	2	450mm X-Axis 8mm Smooth Rod
11	1	440mm Y-Axis-8mm trapez mil
12	2	5mm to 8mm Rigid Shaft Coupler
13	1	Y Axis Motor Mount - Pt1.1
14	12	LM8UU Linear Bearing - 8x15x24mm
15	1	Y Axis Motor Mount - Pt1
16	1	Y Axis Motor Mount - Pt1.2
17	1	XY-Axis Smooth Rod Bearing Idler Mount
18	1	350mm X-Axis 8mm trapez mil
19	2	Y-Axis Idler Mount Pt1.1
20	2	608-ZZ Radial Ball Bearing - 8x22x7mm
21	2	XY Rod Holder - Pt2
22	1	Y Axis Idler Mount - Pt1

Figure B4: Module 4: XY Axis assembly.

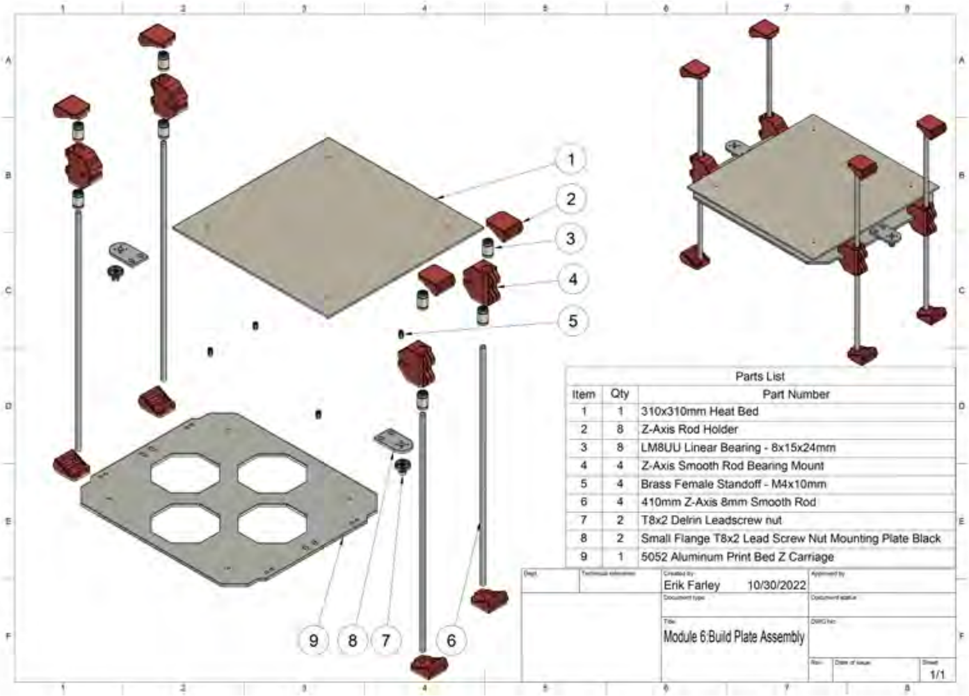


Parts List

Item	Qty	Part Number
1	1	330mm Z-Axis Lead Screw 8mm trapez mil
2	1	5mm to 8mm-Flexible Plum Coupler Shaft
3	1	Z Axis Motor Mount
4	1	Nema 17 (48mm) stepper motor 1.8 Degree
5	1	608-ZZ Radial Ball Bearing - 8x22x7mm
6	1	Z-Axis Threaded Rod Support

Created by: Erik Farley 10/30/2022
Title: Module 5:Z Axis Stepper Motor Assembly
Sheet: 1/1

Figure B5: Module 5: Z Stepper motor assembly.

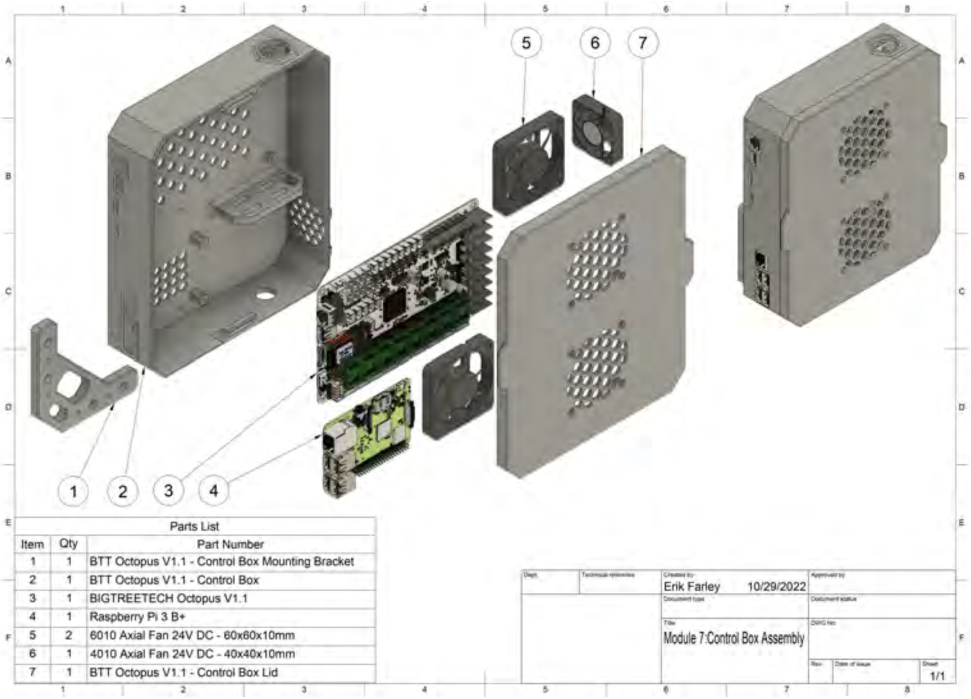


Parts List

Item	Qty	Part Number
1	1	310x310mm Heat Bed
2	8	Z-Axis Rod Holder
3	8	LM8UU Linear Bearing - 8x15x24mm
4	4	Z-Axis Smooth Rod Bearing Mount
5	4	Brass Female Standoff - M4x10mm
6	4	410mm Z-Axis 8mm Smooth Rod
7	2	T8x2 Delrin Leadscrew nut
8	2	Small Flange T8x2 Lead Screw Nut Mounting Plate Black
9	1	5052 Aluminum Print Bed Z Carriage

Created by: Erik Farley 10/30/2022
Title: Module 6:Build Plate Assembly
Sheet: 1/1

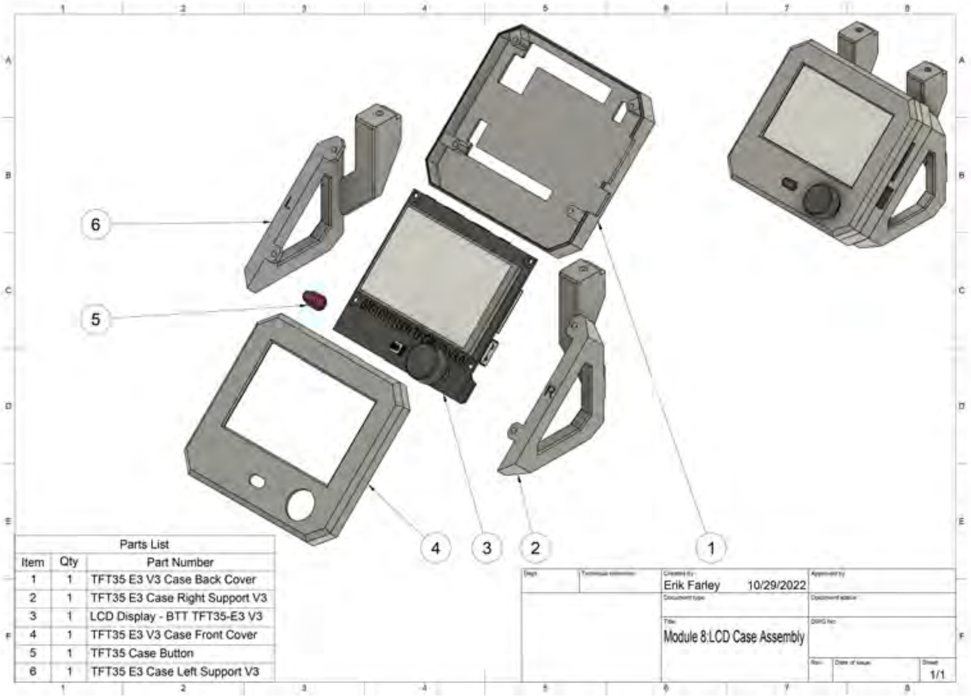
Figure B6: Module 6: Build plate assembly.



Parts List

Item	Qty	Part Number
1	1	BTT Octopus V1.1 - Control Box Mounting Bracket
2	1	BTT Octopus V1.1 - Control Box
3	1	BIGTREETECH Octopus V1.1
4	1	Raspberry Pi 3 B+
5	2	6010 Axial Fan 24V DC - 60x60x10mm
6	1	4010 Axial Fan 24V DC - 40x40x10mm
7	1	BTT Octopus V1.1 - Control Box Lid

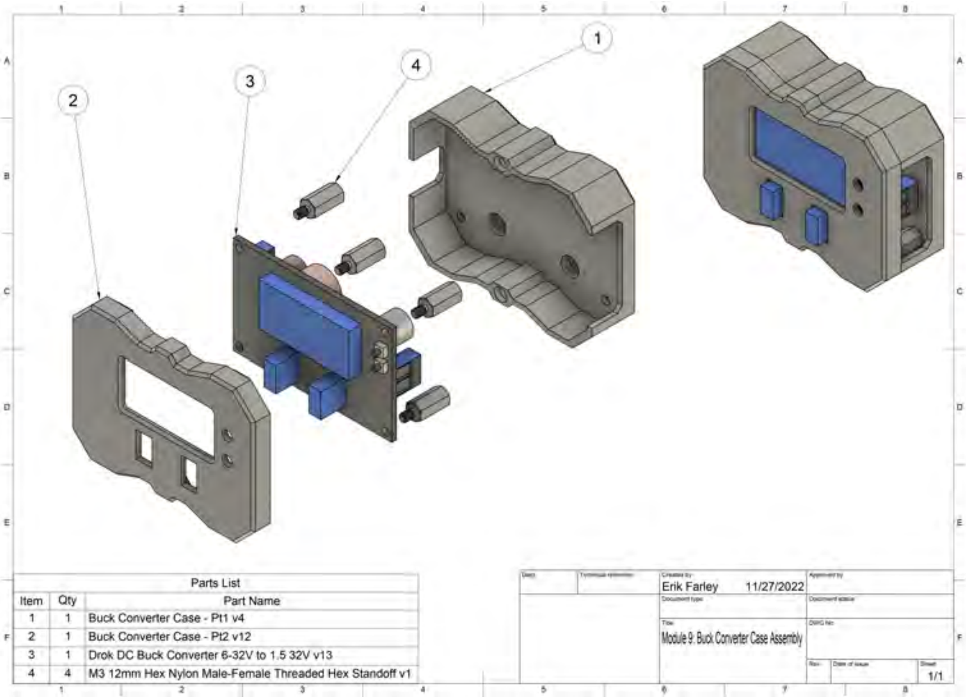
Figure B7: Module 7: Control box assembly.



Parts List

Item	Qty	Part Number
1	1	TFT35 E3 V3 Case Back Cover
2	1	TFT35 E3 Case Right Support V3
3	1	LCD Display - BTT TFT35-E3 V3
4	1	TFT35 E3 V3 Case Front Cover
5	1	TFT35 Case Button
6	1	TFT35 E3 Case Left Support V3

Figure B8: Module 8: LCD case assembly.



Parts List

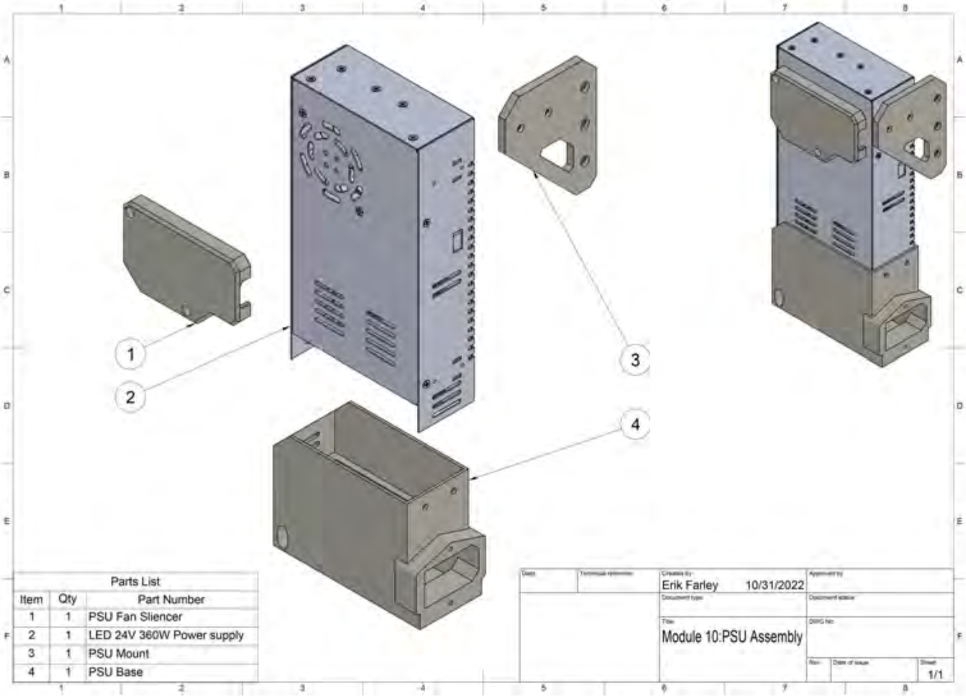
Item	Qty	Part Name
1	1	Buck Converter Case - Pt1 v4
2	1	Buck Converter Case - Pt2 v12
3	1	Drok DC Buck Converter 6-32V to 1.5 32V v13
4	4	M3 12mm Hex Nylon Male-Female Threaded Hex Standoff v1

Created by: Erik Farley 11/27/2022

Title: Module 9: Buck Converter Case Assembly

Sheet: 1/1

Figure B9: Module 9: Buck converter case assembly.



Parts List

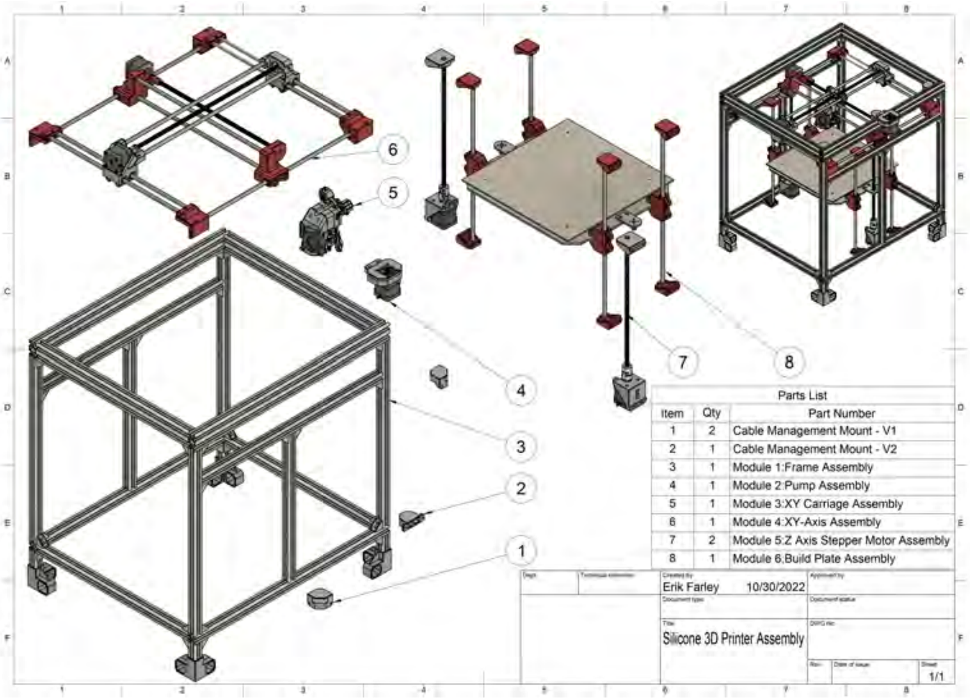
Item	Qty	Part Number
1	1	PSU Fan Sliencer
2	1	LED 24V 360W Power supply
3	1	PSU Mount
4	1	PSU Base

Created by: Erik Farley 10/31/2022

Title: Module 10:PSU Assembly

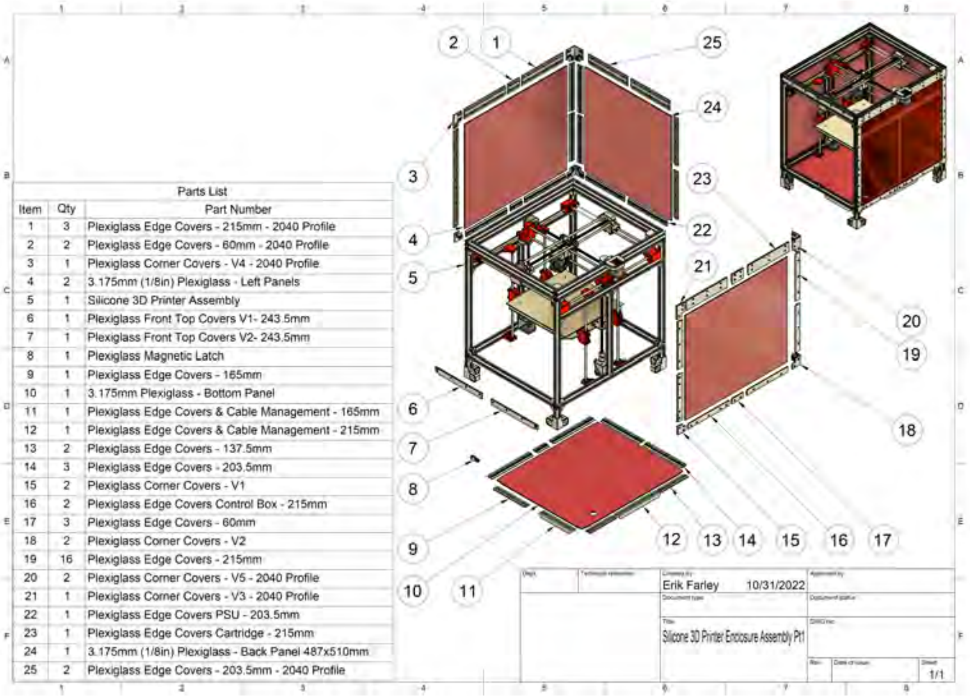
Sheet: 1/1

Figure B10: Module 10: PSU assembly.



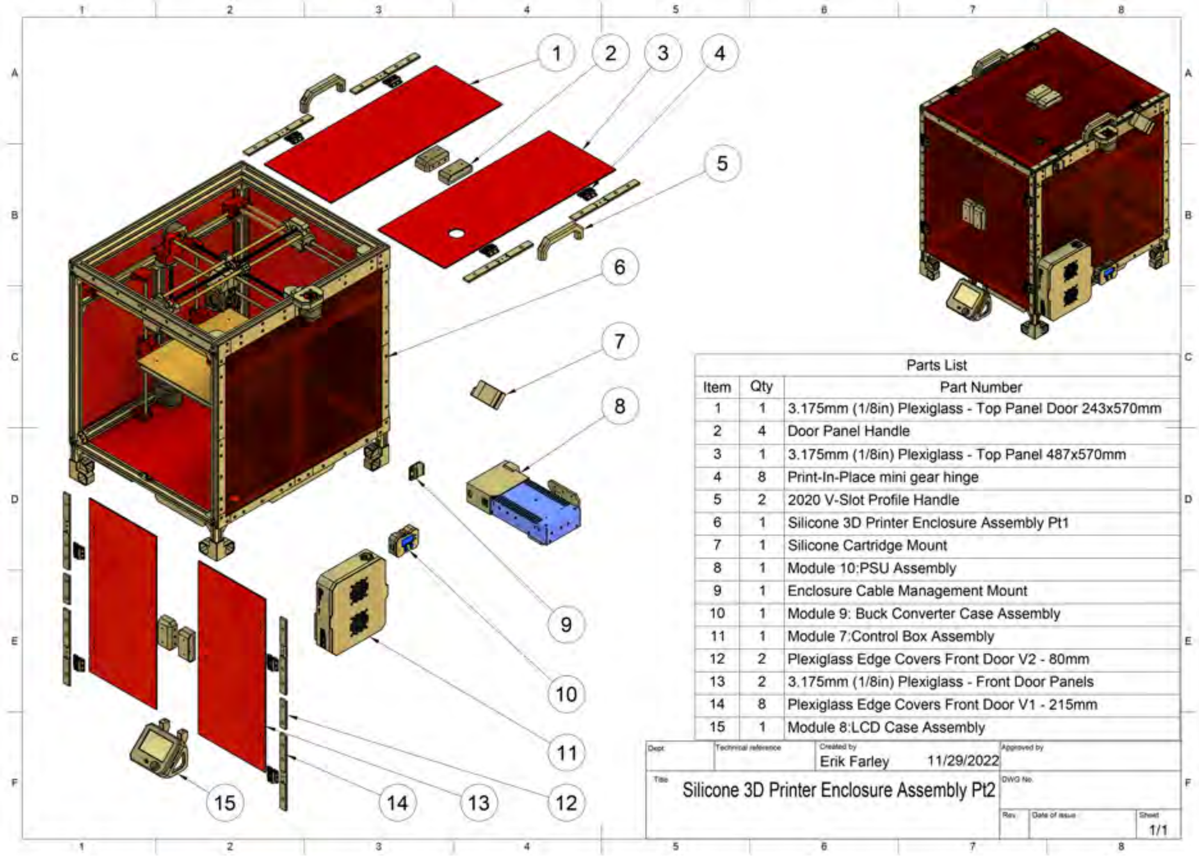
Parts List		
Item	Qty	Part Number
1	2	Cable Management Mount - V1
2	1	Cable Management Mount - V2
3	1	Module 1:Frame Assembly
4	1	Module 2:Pump Assembly
5	1	Module 3:XY Carriage Assembly
6	1	Module 4:XY-Axis Assembly
7	2	Module 5:Z Axis Stepper Motor Assembly
8	1	Module 6,Build Plate Assembly

Figure B11: Silicone 3D printer assembly.



Parts List		
Item	Qty	Part Number
1	3	Plexiglass Edge Covers - 215mm - 2040 Profile
2	2	Plexiglass Edge Covers - 60mm - 2040 Profile
3	1	Plexiglass Corner Covers - V4 - 2040 Profile
4	2	3.175mm (1/8in) Plexiglass - Left Panels
5	1	Silicone 3D Printer Assembly
6	1	Plexiglass Front Top Covers V1- 243.5mm
7	1	Plexiglass Front Top Covers V2- 243.5mm
8	1	Plexiglass Magnetic Latch
9	1	Plexiglass Edge Covers - 165mm
10	1	3.175mm Plexiglass - Bottom Panel
11	1	Plexiglass Edge Covers & Cable Management - 165mm
12	1	Plexiglass Edge Covers & Cable Management - 215mm
13	2	Plexiglass Edge Covers - 137.5mm
14	3	Plexiglass Edge Covers - 203.5mm
15	2	Plexiglass Corner Covers - V1
16	2	Plexiglass Edge Covers Control Box - 215mm
17	3	Plexiglass Edge Covers - 60mm
18	2	Plexiglass Corner Covers - V2
19	16	Plexiglass Edge Covers - 215mm
20	2	Plexiglass Corner Covers - V5 - 2040 Profile
21	1	Plexiglass Corner Covers - V3 - 2040 Profile
22	1	Plexiglass Edge Covers PSU - 203.5mm
23	1	Plexiglass Edge Covers Cartridge - 215mm
24	1	3.175mm (1/8in) Plexiglass - Back Panel 487x510mm
25	2	Plexiglass Edge Covers - 203.5mm - 2040 Profile

Figure B12: Silicone 3D printer assembly.



Parts List		
Item	Qty	Part Number
1	1	3.175mm (1/8in) Plexiglass - Top Panel Door 243x570mm
2	4	Door Panel Handle
3	1	3.175mm (1/8in) Plexiglass - Top Panel 487x570mm
4	8	Print-In-Place mini gear hinge
5	2	2020 V-Slot Profile Handle
6	1	Silicone 3D Printer Enclosure Assembly Pt1
7	1	Silicone Cartridge Mount
8	1	Module 10:PSU Assembly
9	1	Enclosure Cable Management Mount
10	1	Module 9: Buck Converter Case Assembly
11	1	Module 7:Control Box Assembly
12	2	Plexiglass Edge Covers Front Door V2 - 80mm
13	2	3.175mm (1/8in) Plexiglass - Front Door Panels
14	8	Plexiglass Edge Covers Front Door V1 - 215mm
15	1	Module 8:LCD Case Assembly

Dept	Technical reference	Created by	Approved by
		Erik Farley 11/29/2022	

Title: Silicone 3D Printer Enclosure Assembly Pt2
DWG No.:
Rev.:
Date of issue:
Sheet: 1/1

Figure B13: Silicone 3D printer assembly.