Continuous Product Concept Improvement for Integrated Systems: A 3-D Printer Hardware Improvement Case

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Abstract. The advent of globalization and technology has led to proliferation of integrated hardware and software systems such as personal computers, and smartphones while legacy systems such as automobile are increasingly incorporating software technology into their products. The demanding consumer requirements compel companies to deliver improved products on short timelines. Therefore, a partial product improvement process would assist designer in meeting this demand. This paper focuses on uncovering the drawbacks of an integrated system and suggests a methodology to improve its shortcomings. We develop a conceptual framework that highlights the key steps that a designer can consider when performing continuous product development: functional model construction, concept improvement, and improvement strategy. This paper uses a case of an FFF 3D Printer system to demonstrate the method.

1. 1. Introduction
Global markets, rise of internet and more demanding customers has led to increase in complexity of products. To meet these demands, the companies have a large product mix and model mixes. Apple Inc. introduced the iPhone in 2007, with one color and two sizes (4GB and 8GB). In 2020, they have seven different variations of iPhone: five colors and three sizes (64, 128 and 256 GB) or about 105 different devices. This trend is mirrored across various markets - automotive, power tools, biomedical etc.

There is a considerable advantage for firms who have short produc
t development lead times, which can introduce many successive versions of the same product line with increased performance levels. Two important techniques used by firms are product modularization and product platform development, which allow firms to reach high levels of product variety, and at the same time, keep complexity and its related costs at a limited level.

Even with this high demand, there is not structured methodology a designer can utilize to analyze the systems and improve them partially. This paper works within product modularization strategy, as it introduces a new tool which would assist firms to analyze and improve products fractionally. The research outlines three steps to fractional product improvement - Functional Modeling using Design Matrix, Analysis using Design Coupling Sequence, and Improvement Suggestion.

The paper follows the structure as explained further. The background is discussed in detail in Section 2: Research Background. Then the framework and methodology used to understand the couplings and improve the software design is explained in Section 3: Method. Section 4: Case Study: Hardware Design Concept Improvement of 3-D Printer, discusses how the methodology explained in the Method section
can be applied to practical use and the improvements that can be made using this methodology. The Section 5: Results and Discussions discusses and compare the different results obtained using this methodology and how this methodology helps in software conceptual design. Finally, the paper is concluded and the future work that can be done in this domain is suggested in Section 6: Conclusions and Future Work.

### Nomenclature

| Acronym | Description                        |
|---------|------------------------------------|
| DCS     | Design Coupling Sequence           |
| DM      | Design Matrix                      |
| FR      | Functional Requirements            |
| DP      | Design Parameters                  |
| FFF     | Fused Filament Fabrication         |
| FDM     | Fused Deposition Modeling          |

2. **Research Background**

Product development is a network of activities that transform a market opportunity into a product that meets the customer’s needs and the strategic goals of a company [1,2]. Firms consider product development as their competitive lever to survive in a fast-evolving market [3,4]. With the advent of faster manufacturing techniques, global supply chain and internet, there is a need for quicker introduction of better and less costly products [5]. With the advent of multiple generation product lines in many Business to Consumer industries like for instance the technology and automotive, there is constant pressure on the design teams to improve their current products.

The aim of this paper is to establish a systematic analysis for finding improvement opportunities in existing designs. Axiomatic Design Theory (ADT) [2,6], introduced and developed by Nam Suh in 1990 at MIT, is the framework within which the proposed approach has been developed. The AD separates design into four domains – Customer, Functional, Physical and Process [16].

This framework operates in the design space between the functional and physical domains, called Conceptual Design [15]. Zhang et al. [17] define conceptual design as activities to develop the technical specification of a design problem based on customer requirements and provide solutions to satisfy the customer requirement. At this stage, designers are determining functional design of the product and have a large design space to test new innovations and improvement to them.

In the following section, different Axiomatic Design Theory approaches used to perform continuous improvement are discussed.

The ADT articulates that an ideal design has minimal complexity [9]. A pathway to improve existing products is by transforming existing design matrices using matrix manipulation techniques and minimize the complexity. This method cannot be effectively deployed for most real-life products with highly coupled matrices.

In their paper, Qiang et al. [10] use ADT and Design Structure Matrix to modularize products, which would allow designers to substitute sub-assemblies to improve the products. They decomposed a product hierarchically into its functional, physical, and process domains using axiomatic design method. After transformation from design matrix to design structure matrix, suitable design structure matrices of design parameters describing function, structure, and manufacturing process are constructed. This method cannot be effectively deployed more than once for a single product or for a modular product.

Zhong-hang et al. [11] focused on improving the module interface design using TRIZ and AD. It uses AD to analyze the coupling relationship between the module interface and the functional requirements and then uses the conflict solution tool in TRIZ to decouple and propose a suitable connection structure for modular product.

Wang et al. [13,14] introduced the Design Coupling Sequence (DCS), a four-step process to reduce the design complexity during the concept improvement stage. The DCS provides a hierarchical model of design parameters (DPs) to identify the level of coupling in a design matrix. This hierarchical model has two major applications – improving existing design and modularization of system. It defines two
functional sets viz. the independent U-set: which is the collection of functionally dependent concepts, and the coupled C-set: which is the collection of the strongly coupled concepts. Improvements in the conceptual design and partial system conceptual designs can be obtained by using TRIZ or other principles to resolve the complexity by following the execution sequence suggested by the DCS methodology which shows the functional schematics of the design concept.

3. Methodology

The objective of this study is to outline a framework which would enable a designer to improve a system partially. This section outlines the proposed method for partial concept improvement of hardware in an integrated system based on the Design Coupling Sequence (DCS) approach. The procedure is shown in Fig. 1.

![Figure 1. Methodology of Hardware Partial Improvement.](image)

The objective of this study is to come up with a framework which would enable a designer to improve a system partially. should be shifted before picture 1, expanding the argument and explaining from a general standpoint how the proposed method pursues the declared aim.

3.1. Functional Model Construction

DCS is a functional model analysis tool, and the first step is to construct the functional model of the system. A functional model is a structured representation all the components, their functions and their relationship with each other within the modeled system. The functional model can be of a new system or an existing one. In DCS, a design matrix, a type of functional model based on Functional Requirements and Design Parameters is used.

3.1.1. Data Collection. The data collection step is aimed to collect the information about the system, its components, their functions and relationship among them. At the end of data collection phase, the designer should have enough information about the system to construct a design matrix and perform DCS analysis on it.

The four steps of data collection are -
- Identification of major system components.
- Defining the functions of components.
- Relating the components via functional relationships
- Isolating Performance Parameters

3.1.2. Design Matrix (DM) Construction. The Functional Requirements and Design Parameters are described in Axiomatic Design mathematically as a vector [2]. The Design Matrix [DM] describes the relationship between FRs and DPs in a mathematical equation (1)

\[ \{FR\} = [DM]\{DP\} \quad (1) \]

One can construct the design matrix through such relationship.

3.2. Concept Improvement

The multifaceted dynamics of components often may lead to heavily coupled design matrices for complex systems. They can be made simpler or of higher quality using improvement methodologies like
Design Coupling Sequence (DCS). The application of DCS algorithm [13] on a DM can be done in 4 steps.

- Counting the number of ‘X’/Couplings in each FR
- Listing the DPs according to increasing number of couplings
- Examining coupled DPs
- Arranging DPs into sets.

The outcome of the DCS algorithm is the Executable Module (EM), which informs the designer about the precedence and functional sets of different DPs. To execute the improvement of DPs one by one or module by module according to the sequence shown in EM, the design can be improved with the minimal design complexity.

3.3. Improvement Strategies

In the previous section, the EM of the system was obtained, laying out the precedence of the DPs. In this section, the steps a designer needs to take to improve the system are outlined.

3.3.1. Finding Improvement Opportunity. According to DCS approach [13], one improvement opportunity is to resolve strongly coupled DPs, which are indicated by the C-set in the EM. The other improvement opportunity is to break down U-set in the EM to have more U-sets of a design.

3.3.2. DP Selection. The DP selection basically follows the sequence shown in the EM. In each selection, designer needs to think some alternatives of the DP or a group of unsolvable DPs (wrapped by C-set) and should select the design whose system range falls in the design range completely. By using Probability Density Function (Fig. 2), designer can check between system range and design range. If none of alternatives falls in the design range completely, the designer may choose the one which meets the design range most, i.e., the one with the most common area (Acr) shown in Fig. 2.

![Figure 2. Probability Density Plot between FR and DP depicting System and Design Range, and Common Area.](image)

3.3.3. Alternatives Matrix. An alternatives matrix is a tool to compare and assess different alternatives of DPs/C-sets to review the DP selection results. It includes selected DP/C-set, design range, expectation, system range, and the reason of chosen the alternative. An example of the alternatives matrix is shown in Table 7.

3.3.4. Partial Improvement. Since U-sets in EM can be seen as independent design modules, the concept improvement of a large/complex system can be partially improved by improving smaller system separated by U-set. Besides, the system can also be partially improved by fixing the higher precedence DPs. This strategy is explained using the example in Table 1. The designer wants to improve DP21. The
DP_{21} belongs to the U-set U_1 and is preceded by two other DPs, DP_{12} and DP_{22}. The order of improvement for the designer would be DP_{21}, to DP_{12} and then to DP_{22}.

### Table 1. Executable Module of a Sample System

| U-set | Row | Sequence          |
|-------|-----|-------------------|
| U_1   | 1   | DP_{22} → DP_{12} → \{DP_{11}, DP_{31}\} |
|       | 2   | \downarrow DP_{21} |
| U_2   | 3   | DP_{32}           |

The designer would now select the DPs from the alternative’s matrix. When the sequence is followed, the design range for the DP_{22} would be highest, followed by DP_{12} and DP_{21}. This means that progressively as a designer makes decisions, the options of alternatives decrease for DPs with lower precedence.

This step would result in one of the two possibilities –

1. Satisfaction of all DPs – If the designer is able to satisfy the selection of alternative DPs using the above-mentioned framework, they can implement partial changes in the system.

2. Unable to satisfy all DPs – If the designer is unable to satisfy the selection of alternative DPs, they would have to change the U-Set to implement the changes. It can be either done by choosing a different set of DPs or by changing the ES of the U-Set.

The designer has to select one Execution Sequence (ES) from all the possible EM.

### 4. Application of Hardware Improvement in a 3-D printer case

This application shows how to improve an FFF Printer like Prusa i3 MK3S within the proposed method. The selection was made due to expertise of authors in field, and availability of documentation of its components and assembling process.

#### 4.1. Functional Model Construction

##### 4.1.1. Data Collection

In the first step, all the system components were identified, listed and categorized according to the function they performed. The inferences for the components were based on system architecture diagrams as shown in Fig. 3. These components are classified as Design Parameters or DPs. In the following table, the highest-level DPs have been outlined.
The third step consists the identification of the relationship between FRs and DPs according to their interaction (i.e., functional coupling) including physical, material, information and energy with other components. In the 3-D printer case, the functional couplings were verified by interview with subject matter expert.

In the fourth step, the performance parameters of each component or DP were identified. They would be used in the latter half while identifying improvement strategies.

### 4.1.2. Design Matrix Construction

The data collection resulted in a rectangular design matrix for the FDM 3D Printer of 25 by 25 (Table 3). There are 139 couplings – 26 diagonal and 113 off-diagonal elements (Fig. 4).

#### Table 3. List of Functional Requirements and Design Parameters

| # | FR                                      | DP                     |
|---|-----------------------------------------|------------------------|
| 11| Supply Power to System                  | Power Supply           |
| 12| Turn the system on or off               | Power Switch           |
| 21| Control Mechanical Commands and Verify Sub-System Status | Command and Monitor Circuit |
| 22| Supply Power to Printer Components      | Power Convertor        |
| 31| Display Printing Information            | I/O Interface          |
| 32| Enable User to input Information        | Data Input             |
| 33| Send print data                         |                        |
| 41| Store raw material                      | Material Storage Space |
| 42| Transport material                      | Material Conveyor      |
| 51| Feed Material                           | Filament Extruder      |
| 54| Shape and Extrude Melt                  | Nozzle Head            |
Since this case was designed to show the partial improvement (the hardware improvement only) of a FFF printer, the DM was modified by following the proposed method. We analysed the couplings among the modules within the DCS method to determine the precedence and obtained the results as shown in Fig. 5.

**Figure 4.** Design Matrix for FFF 3D Printer

| OP ↓ | Design Matrix of FFF 3D Printer |
|------|-------------------------------|
|      | FR   | 11 | 12 | 21 | 22 | 31 | 33 | 41 | 42 | 51 | 54 | 52 | 55 | 53 | 611 | 612 | 613 | 621 | 622 | 623 | 631 | 632 | 633 | 71 | 72 | 73 |
|      | 11   | X  | X  | X  |    |    |    |    |    |    |    |    |    |    |    |    |    |    |    |    |    |    |    |    |    |    |    |
|      | 12   | X  | X  |    |    |    |    |    |    |    |    |    |    |    |    |    |    |    |    |    |    |    |    |    |    |    |    |
|      | 21   | X  | X  | X  | X  | X  | X  | X  | X  | X  | X  | X  | X  | X  | X  | X  | X  | X  | X  | X  | X  | X  | X  | X  | X  | X  | X  |
|      | 22   | X  | X  | X  | X  | X  | X  | X  | X  | X  | X  | X  | X  | X  | X  | X  | X  | X  | X  | X  | X  | X  | X  | X  | X  | X  | X  |
|      | 31   | X  | X  |    |    |    |    |    |    |    |    |    |    |    |    |    |    |    |    |    |    |    |    |    |    |    |    |
|      | 32   | X  | X  |    |    |    |    |    |    |    |    |    |    |    |    |    |    |    |    |    |    |    |    |    |    |    |    |
|      | 33   | X  | X  | X  |    |    |    |    |    |    |    |    |    |    |    |    |    |    |    |    |    |    |    |    |    |    |    |
|      | 41   |    |    |    |    |    |    |    |    |    |    |    |    |    |    |    |    |    |    |    |    |    |    |    |    |    |    |
|      | 42   |    |    |    |    |    |    |    |    |    |    |    |    |    |    |    |    |    |    |    |    |    |    |    |    |    |    |
|      | 51   |    |    |    |    |    |    |    |    |    |    |    |    |    |    |    |    |    |    |    |    |    |    |    |    |    |    |
|      | 52   |    |    |    |    |    |    |    |    |    |    |    |    |    |    |    |    |    |    |    |    |    |    |    |    |    |    |
|      | 53   |    |    |    |    |    |    |    |    |    |    |    |    |    |    |    |    |    |    |    |    |    |    |    |    |    |    |
|      | 54   |    |    |    |    |    |    |    |    |    |    |    |    |    |    |    |    |    |    |    |    |    |    |    |    |    |    |
|      | 55   |    |    |    |    |    |    |    |    |    |    |    |    |    |    |    |    |    |    |    |    |    |    |    |    |    |    |
|      | 56   |    |    |    |    |    |    |    |    |    |    |    |    |    |    |    |    |    |    |    |    |    |    |    |    |    |    |
|      | 57   |    |    |    |    |    |    |    |    |    |    |    |    |    |    |    |    |    |    |    |    |    |    |    |    |    |    |
|      | 58   |    |    |    |    |    |    |    |    |    |    |    |    |    |    |    |    |    |    |    |    |    |    |    |    |    |    |
|      | 59   |    |    |    |    |    |    |    |    |    |    |    |    |    |    |    |    |    |    |    |    |    |    |    |    |    |    |
|      | 611  |    |    |    |    |    |    |    |    |    |    |    |    |    |    |    |    |    |    |    |    |    |    |    |    |    |    |
|      | 612  |    |    |    |    |    |    |    |    |    |    |    |    |    |    |    |    |    |    |    |    |    |    |    |    |    |    |
|      | 613  |    |    |    |    |    |    |    |    |    |    |    |    |    |    |    |    |    |    |    |    |    |    |    |    |    |    |
|      | 621  |    |    |    |    |    |    |    |    |    |    |    |    |    |    |    |    |    |    |    |    |    |    |    |    |    |    |
|      | 622  |    |    |    |    |    |    |    |    |    |    |    |    |    |    |    |    |    |    |    |    |    |    |    |    |    |    |
|      | 623  |    |    |    |    |    |    |    |    |    |    |    |    |    |    |    |    |    |    |    |    |    |    |    |    |    |    |
|      | 631  |    |    |    |    |    |    |    |    |    |    |    |    |    |    |    |    |    |    |    |    |    |    |    |    |    |    |
|      | 632  |    |    |    |    |    |    |    |    |    |    |    |    |    |    |    |    |    |    |    |    |    |    |    |    |    |    |
|      | 633  |    |    |    |    |    |    |    |    |    |    |    |    |    |    |    |    |    |    |    |    |    |    |    |    |    |    |
|      | 71   |    |    |    |    |    |    |    |    |    |    |    |    |    |    |    |    |    |    |    |    |    |    |    |    |    |    |
|      | 72   |    |    |    |    |    |    |    |    |    |    |    |    |    |    |    |    |    |    |    |    |    |    |    |    |    |    |

**52.** Melt Material  **Heater**

**55.** Cool the Hot Side  **Cooling System**

**53.** Measure Temperature of Hot Side  **Extruder Thermocouple**

**611.** To move along X-Axis  **X Positioning Drive**

**612.** Restrict Motion in X axis  **Limit Switch**

**613.** To trigger motion of extruder in X-Axis  **Actuator**

**621.** To move along Y-Axis  **Y Positioning Drive**

**622.** Restrict Motion in Y-Axis  **Limit Switch**

**623.** To trigger motion of extruder in Y Axis  **Actuator**

**631.** To move along Z-Axis  **Z positioning drive**

**632.** Restrict Motion in Z-Axis  **Limit Switch**

**633.** To trigger motion of extruder in Z Axis  **Actuator**

**71.** Support printing product  **Base Plate**

**72.** Prevent Warping  **Base Plate Heater**

**Base Plate Thermocouple**
4.2. Concept Improvement

Once the design matrix was obtained, the DCS methodology was applied. The executable modules of the FFF 3-D printer were obtained (Table 4) to show the functional structure of the modified design matrix.

The execution module gives us 4 U-sets and 2 C-sets. The 4 U-Sets allow the designers to compartmentalize design improvement process. Effectively, a designer target specific U-sets to improve without sacrificing the performance of other U-sets. From the U-sets, it is clearly visible that U2, U3, and U4 containing – Base Plate Module, Display Module and Power Module can be improved independently whereas all other modules are encompassed within U1.

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4.3. Improvement Strategy

4.3.1. Finding Improvement Opportunity

The improvement opportunities for FFF printers were outlined in research papers. The primary drawbacks of FFF printing are low dimensional tolerance of final parts and slow printing times.
Therefore, our improvement objective is to improve the printer which produces prints with high dimensional tolerance at a faster rate.

As shown in Table 4, there are two C-sets ({DP51, DP52} and {DP72, DP73}) in the EM, and they are the improvement opportunities of this design. In addition, U1 should be the main system to be improved as it has the most coupled DPs to be break down.

4.3.2. DP Selection

The next step was to identify the DPs whose performance needs to be improved. A Root Cause Analysis of an FFF printer was analyzed to understand the parameters which affect the build time and dimensional accuracy. The major parameters from RCA which can be improved by altering the system are –Layer Thickness, Air Gap, Extrusion Temperature, and Print Speed.

The DPs which affect the parameters are Filament Module, Extruder Module and Control Module. In Table 5, the parameters and their interaction with DPs are outlined.

| Table 5. Design Parameter Selection. |
|---------------------------------------|
| DP ↓ | Performance Factors | Printing Time | Dimensional Accuracy |
| 42 | Material Conveyor | Performance affects printing time | No Affect |
| 51 | Filament Extruder | Component Weight affects Print Time | Component Weight affects Dimensional Accuracy |
| 54 | Nozzle Head | Component Weight affects Print Time | Component Weight affects Dimensional Accuracy |
| 52 | Heater | Component Weight affects Print Time | Component Weight affects Dimensional Accuracy |
| 55 | Cooling System | Component Weight affects Print Time | No Affect |
| 53 | Extruder Thermocouple | Component Weight affects Print Time | No Affect |
| 61 | X Positioning Drive | Component Performance affects printing time | Performance affects dimensional accuracy |
| 62 | Y Positioning Drive | Component Performance affects printing time | Performance affects dimensional accuracy |

Then the design range were determined as shown in Table 6. According to the design ranges of the sequenced DP/C-est, the designs of each alternatives were selected.
Table 6. Design Parameter Target and Design Ranges for DP Selection

| Sequence | DP                  | Target Parameter          | Design range          |
|----------|---------------------|---------------------------|-----------------------|
| 41       | Material Storage Space | Ease of accessibility     | 90-100%              |
| {51, 52} | Filament Extruder / Heater | Feed rate / Efficiency    | 80-100%              |
| 42       | Material Conveyor   | Tension in the filament   | 80-100%              |
| 611      | X Positioning Drive | Precision                 | -0.05 to + 0.05 mm   |
| 612      | X Limit Switch      | Responsiveness            | 5-10 micron          |
| 621      | Y Positioning Drive | Precision                 | +/- 0.01 +/- 0.05    |
| 622      | Y Limit Switch      | Responsiveness            | 5-10 micron          |
| 631      | Z Positioning Drive | Precision                 | +/- 0.01 +/- 0.05    |
| 632      | Z Limit Switch      | Responsiveness            | 5-10 micron          |
| 54       | Nozzle Head         | Withstand high temperature | 200 - 400 deg C     |
| 613      | X Actuator          | Speed                     | 1000-2000 rpm        |
| 623      | Y Actuator          | Speed                     | 1000-2000 rpm        |
| 633      | Z Actuator          | Speed                     | 1000-2000 rpm        |
| 53       | Extruder Thermocouple | Accuracy and Response time | 1deg/ 5 sec         |
| 55       | Cooling System for Heater | Heat dissipated         | 5 - 15W/deg C        |

4.3.3. Alternatives Matrix

An Alternatives Matrix was built with Target Parameters and Design Range. The alternatives matrix with all the possible alternatives, is listed in Table 7. The alternatives selection table outlines the alternatives selected and the reason for selection.

As shown in Table 7, the scope of improvement would be to increase the dimensional accuracy of the printer, and as a result, the DPs affected, in sequence of precedence are – DP611, DP612, DP613, DP621, DP622, DP623, DP51, DP54, DP52.

Table 7. Alternatives Matrix of the FFF 3-D Printer Hardware System

| Sequence | DP611 | (DP51, DP52) | DP621 | DP622 | (DP631, DP632) | DP623 | DP54 | (DP613, DP623) |
|----------|-------|--------------|-------|-------|----------------|-------|------|----------------|
| Selection | Mounted Spool placed on top | Drive gear with Idler gear with Resistive heater | PTFE Tube | Linear rails | Linear rails | Stopper limit switch | Rack and Pinion | Stopper limit switch |
| Design range | 90-100% | 90-100% | PTFE Tube | 5-10 micron | +/- 0.01 +/- 0.05 | 5-10 micron | High Performance | 10 micron |
| Expectation | Does not affect accuracy | Low Weight and High Performance | Does not affect accuracy | High Performance | High Performance | High Performance | High Performance | High Performance |
| System Range | 95-100% | 95-100% | Does not affect accuracy | 5-10 micron | - 0.03 to + 0.03 micron | 0.0254 mm | 5-10 micron | Does not affect accuracy |
| Reason | Standard Configuration | Simple mechanism and High Efficiency | Standard Configuration | Fast Response Time And Low cost | Highest accuracy | Standard Configuration | Standard Configuration | Standard Configuration |
| Sequence | DP622 | (DP631, DP632) | DP623 | DP54 | (DP613, DP623) |
| Selection | Snap action limit switch | Rack and Pinion | Stopper limit switch | Screwable Nozzle | Servo Motor | Servo Motor | Servo Motor | Servo Motor |
| Design range | 5-10 micron | +/- 0.01 +/- 0.05 | 5-10 micron | 200 - 400 deg C | 1000-2000 rpm | 1000-2000 rpm | 1000-2000 rpm | 1000-2000 rpm |
| Expectation | High Performance | Does not affect accuracy | Does not affect accuracy | Low Weight and High Performance | Accuracy at High Speed | Accuracy at High Speed | Accuracy at High Speed | Accuracy at High Speed |
| System Range | 5-10 micron | 0.0254 mm | 10 micron | 280 deg C | 0.33 degree/ 1000- 5000 rpm | 0.33 degree/ 1000- 5000 rpm | 0.33 degree/ 1000- 5000 rpm | 0.33 degree/ 1000- 5000 rpm |
| Reason | Fast Response Time And Low cost | Standard Configuration | Standard Configuration | Low Weight and High Efficiency | Highest accuracy and High Speed | Highest accuracy and High Speed | Highest accuracy and High Speed | Highest accuracy and High Speed |
4.3.4. Partial Improvement
In the final step, DP Alternatives would be selected from the Alternative Matrix. If the system range of the Alternative falls within the design range of the DP, the alternative is selected. If it is outside the design range, either another alternative is chosen or change the ES of the U-Set. The alternatives (summarized below) selected satisfied the given design range of DP.

Table 8. Selected Alternatives of the FFF 3-D Printer Hardware System

| Sequence | DP                  | Alternative | Design Range | System range |
|----------|---------------------|-------------|--------------|--------------|
| 41       | Material Storage    | Spool covered with a box on four sides with open lid on top | 90-100% | 90-100% |
| [51, 52] | Filament Extruder / Drive gear with idler gear with Resistive heater | 80-100%/ 90-100% | 85-95% / 95-100% |
| 42       | Material Conveyor   | PTFE Tube   | 80-100%      | 85-95%       |
| 611      | X Positioning Drive | High accuracy Linear rails | -0.05 to + 0.05 mm | 0.03 to + 0.03 mm / 5 m/s |
| 612      | Y Limit Switch      | Snap action limit switch | 5-10 micron | 5-10 micron / Easily available and lowest cost |
| 621      | Y Positioning Drive | High accuracy Linear rails | +/- 0.01 +/- 0.05 | - 0.03 to + 0.03 mm |
| 622      | Y Limit Switch      | Snap action limit switch | 5-10 micron | 10 micron / Easily available and lowest cost |
| 631      | Z Positioning Drive | Ball screw | +/- 0.01 +/- 0.05 | +0.02 mm |
| 632      | Z Limit Switch      | Snap action limit switch | 5-10 micron | 10 micron / Easily available and lowest cost |
| 54       | Nozzle Head         | Screwsable small Nozzles | 200 - 400 deg C | 280 deg C / Lightweight |
| 613      | X Actuator          | Stepper Motor | 1000-2000 rpm | 1.8 degree and no constant feedback / 1000-1500 rpm |
| 623      | Y Actuator          | Stepper Motor | 1000-2000 rpm | 1.8 degree and no constant feedback / 1000-1500 rpm |
| 633      | Z Actuator          | Stepper Motor | 1000-2000 rpm | 1.8 degree and no constant feedback / 1000-1500 rpm |

5. Discussion
The DCS Sequence helps a designer identify the scope for improvements sequentially such that they do not affect other parameters. This helps to reduce reiteration of complete design, and to & fro iterations between DPs. Once the modified DM was obtained, the next step is to assemble a list of design parameters which would solve the functional requirements. Each FR can be satisfied using different DPs. The acumen of a designer would enable them to choose an alternative which would perfectly satisfy the need. However, a designer is limited by their knowledge of the alternatives and thus sometimes they may overlook selecting a DP because they simply do not have enough knowledge about it. Thus, we can see from the modified DM that once we improve DP41 and move to {DP51, DP52}, we need to think of alternatives and solutions that are compatible with the selected DP41 and then move on further to DP42 and so on. Therefore, this method helps to sequentially improve the design of the product. To improve the design process, we use selection methods which would enable designers without considerable knowledge about a field to make and evaluate design selection.

This major observations from the case study are -
1. From the ES, we can clearly identify that Filament Module, Extruder Module and Control Module have higher precedence and thus a larger design space/ flexibility. Therefore, the designer should develop these modules first, followed by other modules.
2. We rearrange the design matrix according to the execution sequence. From the design matrix, we can clearly identify that there is a central module comprising of filament, extruder and control module. Also, there is an auxiliary module comprised of power, base plate and display module. Between the two modules, we can clearly see that there are relations/ couplings.
3. From the DM in Figure 9, we can see that the central module has the highest number of couplings and thus, most of the improvements will come from this section. Whereas the auxiliary module is a decoupled design and has less scope for improvements.

The two major improvements which can be implemented from the case study are -
1. For {DP51, DP52} if we consider it as a module and select the best alternative then we can eliminate DP42, which is a better solution from downstream perspective. But if we solve this coupling with TRIZ then it suggests Segmentation principle through which we can separate the extruder and
heater (Bowden extruder) which helps to eliminate couplings between DP51, DP52 and Module 6, and thus, is a better solution from upstream perspective.

2. If we can eliminate the C-Set by removing the couplings between DP72 and DP73, then we can have a more ideal solution.

Yet some improvements are not feasible, and we need to stick to the original design because they require change in the controller module which was fixed earlier to all the parameters.

6. Conclusion and Future Work
This paper outlines a method to design, analyze and enhance a hardware system. The first step demonstrates the process of information collection to build a functional model. The information collecting step outlines the relevant data which would be required for construction of a system model. This was followed by sketching out the steps to make a Design Matrix (DM) to visualize the system. The second step, Design Coupling Sequence (DCS) methodology was used to generate an Execution Module (EM), a hierarchical structure of the functional model. The DCS methodology helps the designer determine the best sequence of functional couplings to reduce the complexity as much as possible. It also allows the designer to uncover improvement opportunities in the system. The third step, we outline improvement strategy to partially improve the design of the system. This begins with understanding the current drawbacks in the product/system and mapping them to the causal DPs. Once the improvement DPs have been highlighted, the EM would be used to define the improvement strategy. This strategy would suggest all the DPs which need to be modified to improve the performance of the product. In the next step, a procedure for comparing different alternatives of DPs is outlined and method for implementing the modified DPs. Finally, this methodology was explained using a case study on an FFF 3D printer.

From the case study, a precedence in designing sub-systems was setup, with highest precedence given to the Filament Module, Extruder Module and Control Module. They should have access to largest design space and be developed first, followed by other modules. This precedence should allow designers to partially improve modules for each generation of product without the necessity to redesign the product.

The design matrix showed that a 3D Printer can be separated into two modules - a central module (comprising of filament, extruder and control module) and an auxiliary module (comprised of power, base plate and display module). This should help companies design platforms for their products and reduce their development cycle times and manufacturing costs.

Finally, presence of large number of couplings within Control Module suggests that the current generation of products have high complexity and in future, largest number of improvements will come from this section.

The future works should focus on application of DCS on integrated systems. The current set of methodology is designed to work with homogenous modules like physical or non-physical components. A comprehensive methodology which would allow the designer to compare all the elements of a system – hardware and software and that would enable them to make better decisions.

References
[1] Gassmann, O. & Von Zedtwitz, M. Organization of industrial R&D on a global scale. R D Manag. 28, 147–161 (1998).
[2] Suh, N. P. Engineering Design Axiomatic Design Theory for Systems. Res. Eng. Des. 10, 189–209 (1998).
[3] Van Hoek, R. I., Vos, B. & Commandeur, H. R. Restructuring European Supply Chains by Implementing Postponement Strategies. Long Range Plann. 32, 505–518 (1999).
[4] Gassmann, O. & Von Zedtwitz, M. New concepts and trends in international R&D organization. Res. Policy 28, 231–250 (1999).
[5] Fine, C. & Whitney, D. Is the make-buy decision process a core competence? MIT Cent. Technol.
Policy Ind. Dev. 1–31 (2002).

[6] Farid, A. & Suh, N. Axiomatic Design in Large Systems. Axiomatic Design in Large Systems (2016). doi:10.1007/978-3-319-32388-6.

[7] Jang, B. S., Yang, Y. S., Song, Y. S., Yeun, Y. S. & Do, S. H. Axiomatic design approach for marine design problems. Mar. Struct. 15, 35–56 (2002).

[8] Zhu, A., He, S., He, D. & Liu, Y. Conceptual Design of Customized Lower Limb Exoskeleton Rehabilitation Robot Based on Axiomatic Design. Procedia CIRP 53, 219–224 (2016).

[9] Suh, N. P. Complexity in engineering. CIRP Ann. - Manuf. Technol. 54, 46–63 (2005).

[10] Cheng, Q., Zhang, G., Gu, P. & Shao, X. A product module identification approach based on axiomatic design and design structure matrix. Concurr. Eng. Res. Appl. 20, 185–194 (2012).

[11] Bai, Z. H., Zhang, S., Ding, M. & Sun, J. G. Research on product innovation design of modularization based on theory of TRIZ and axiomatic design. Adv. Mech. Eng. 10, 1–15 (2018).

[12] Thielman, J. & Ge, P. Applying axiomatic design theory to the evaluation and optimization of large-scale engineering systems. J. Eng. Des. 17, 1–16 (2006).

[13] Wang, C. Y. & Lu, S. C. Y. Managing Functional Coupling Sequence to Decrease Complexity and Increase Modularity in Conceptual Design. MATEC Web Conf. 223, 1–9 (2018).

[14] Wang, C. & Lu, S. C. Managing Functional Coupling Sequences To Reduce Design Complexity During Concept Improvements. ASME 2015 Int. Des. Eng. Tech. Conf. Comput. Inf. Eng. Conf. 1–7 (2017).

[15] Fan, L. X., Cai, M. Y., Lin, Y., & Zhang, W. J. (2015). Axiomatic design theory: Further notes and its guideline to applications. International Journal of Materials and Product Technology, 51(4), 359–374

[16] Zhang, W. J., Li, J. W., & Zettl, B. (2012). Classification of design theories and methodologies for effective industrial applications. Proceedings of the 2012 7th IEEE Conference on Industrial Electronics and Applications, ICIEA 2012, (1), 1255–1260.

[17] Zhang, R., Cha, J., & Lu, Y. (2007). A conceptual design model using axiomatic design, functional basis and TRIZ. IEEM 2007: 2007 IEEE International Conference on Industrial Engineering and Engineering Management, 1807–1810.