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Application of the VDI 2221 method in the design of 3D printer machines utilizing additive manufacturing technology

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ABSTRACT
In the era of Industry 4.0, digital transformation integrates advanced technologies such as the Internet of Things (IoT), artificial intelligence, and data-driven manufacturing, driving advancements in science and technology. Within this framework, this study focuses on the design and fabrication of a cantilever-type 3D printer aimed at producing a prototype capable of efficient and functional 3D object printing. Additive Manufacturing (AM) technology, particularly Fused Deposition Modeling (FDM), enables the conversion of digital designs into physical products through the layer-by-layer deposition of material. The 3D printer is designed using the VDI 2221 methodology, which encompasses four key phases: task clarification, conceptual design, embodiment design, and detailed design. A key consideration during the design process is the use of filaments derived from plastic bottle waste to mitigate environmental impact. The results identify the Cartesian model variant (Variant 1) as the optimal solution, selected based on functional performance, cost efficiency, and ease of assembly. This machine achieves nozzle temperatures up to 270°C and bed temperatures up to 80°C, with a total production cost of Rp 3,657,000.00. These findings demonstrate the potential of 3D printing technology to advance plastic waste recycling and promote the development of more sustainable 3D printing solutions.

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1. INTRODUCTION

The development of Industry 4.0 to date has fundamentally transformed various manufacturing processes. This transformation has created more advanced production systems through the integration of interconnected automation systems. One of the key foundations in industrial development is Additive Manufacturing (AM), more commonly known as 3D printing. The main advantages of AM technology include rapid prototyping and design flexibility [1], [2].

The use of AM technology enables the creation of objects from digital models layer by layer. AM encompasses several techniques, but Fused Deposition Modeling (FDM) is the most widely used method both in industrial and personal applications. This is due to its relatively low cost and ease of use [3]. FDM begins by extruding heated thermoplastic filament through a nozzle to form the desired object in a layer-by-layer manner[4], [5].

With the growing use of AM technology—especially the FDM method—there are increasing concerns about the environmental impact caused by conventional filament materials. The most commonly used filaments in FDM are Acrylonitrile Butadiene Styrene (ABS) and Polylactic Acid (PLA). These conventional filaments are typically made from virgin plastics derived from fossil fuels (petroleum or natural gas), which makes them dependent on non-renewable resources. Furthermore, when the printed objects are no longer used or become damaged, they often end up in landfills or pollute the environment, since many plastics are not naturally biodegradable [6]. Although PLA is considered a bioplastic, its decomposition process requires specific conditions that are rarely found in natural environments, which still poses a waste management issue [6], [7]. Therefore, there is an urgent need to develop more environmentally friendly and sustainable alternative filaments.

To meet the need for alternative filaments and reduce the environmental impact of AM technology, a strategic approach has been introduced by recycling plastic bottle waste into filament material suitable for use in FDM [5]. However, there are still several limitations in the development of 3D printers capable of effectively and practically processing these alternative filaments. Existing studies and practices have yet to focus on designing 3D printer machines that are optimized for the specific characteristics of recycled plastic bottle filaments—especially considering the recycling process using pultrusion machines, which often results in inconsistent filament diameter and material quality [7]. Therefore, to address this issue, the development of a 3D printer using the VDI 2221 method is proposed. This method ensures a comprehensive product development process, from design to machine construction, enabling the machine to work not only with conventional filaments but also with alternative filaments made from recycled plastic bottles [4].

The Verein Deutscher Ingenieure (VDI) has developed the VDI 2221 guideline, which provides a systematic methodology for product development. This guideline consists of several general work stages characterized by a transparent, rational, and industry-independent approach [8]. The VDI 2221 method is a structured design framework that supports systematic product development by guiding designers through four key stages: task clarification, conceptual design, embodiment design, and detailed design. This approach enhances the learning process and ensures thorough and methodical progress from initial needs to final product specifications [9], [10].

Although many studies have discussed the development of alternative filaments from plastic bottle waste, most of them do not focus on optimizing the 3D printer used. Moreover, studies that integrate a systematic design approach for the development of 3D printers are still very limited [11]. This gap highlights the need for research that not only considers the sustainability of alternative filament materials, but also provides a 3D printer machine that can adapt to the variability of these materials. This research aims to develop a design and construction of a 3D printer using the VDI 2221 method, optimized for the use of alternative filaments made from recycled plastic bottles—thereby supporting sustainability in the application of Additive Manufacturing technology in the Industry 4.0 era.

2. MATERIALS AND METHODS

The design of the 3D printing machine incorporates various materials and components, including aluminum profiles, acrylic, stepper motors, pulleys, tensioners, timing belts, lead screws, hot ends, heat beds, control boards, and more[12]. The machine frame is designed using aluminum or acrylic profiles, with a stepper motor serving as the drive system, transferring motion via a timing belt combined with a lead screw or linear guide [13]. All electrical components, including motor movements, limit switches, fans, and the temperatures of the nozzle and bed, are managed through the control board [7].

The VDI 2221 method comprises four phases: task classification, product concept design, product form design, and detailed design. The first phase involves gathering information and data regarding the design requirements and constraints, which are then formulated into clear specifications. In the second phase, problem abstraction and the development of function structures are conducted to identify principle solutions for addressing variant problems. The outcome of this phase is a set of basic solutions or product concepts. The third phase focuses on creating initial forms based on the previously determined solution principles, followed by selecting the most suitable solution according to technical, economic, and other relevant criteria. Finally, the detailed design phase produces comprehensive documentation, including machine drawings, detailed component drawings, parts lists, material specifications, operating systems, and other relevant documents necessary for evaluation and implementation [14].

A flow diagram can be used to depict the phases above, organizing the VDI 2221 method into seven stages for clearer insight, as shown in Figure 1.

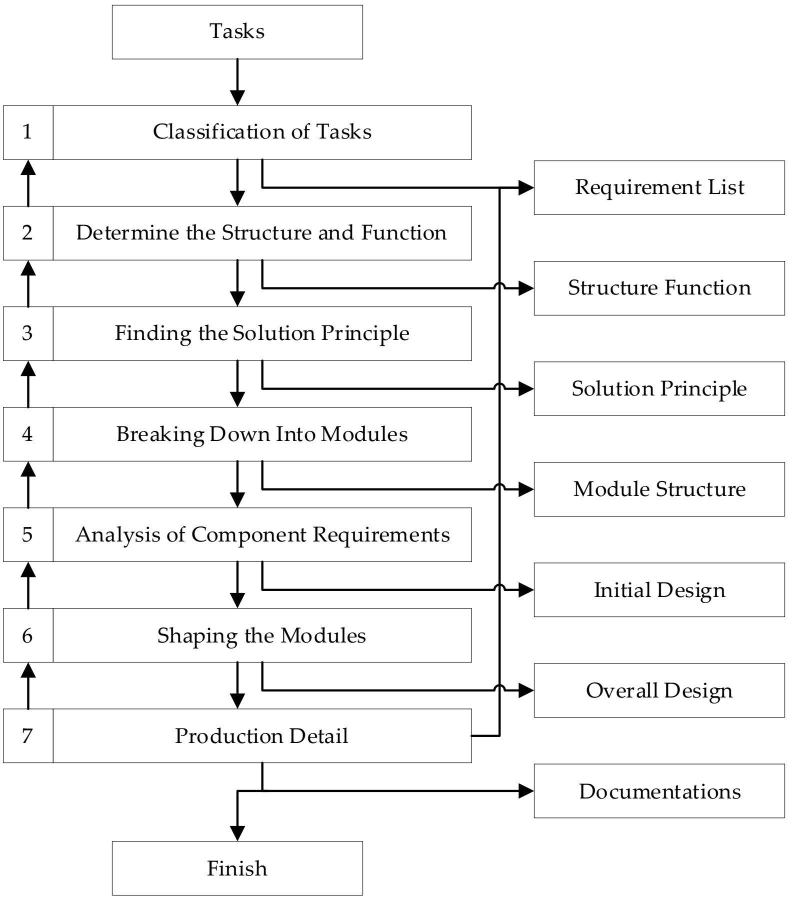


Figure 1.VDI 2221 method flowchart

3. RESULTS

The design planning of the 3D printing machine aims to support the recycling approach developed through the pultrusion machine, which produces filament material from PET plastic bottle waste labeled with code 1. This filament is then processed using the 3D printing machine to fabricate objects or products with economic value. The design process of the 3D printing machine follows the VDI 2221 method, starting with task classification that involves gathering information on the basic requirements and goals for the 3D printer design, ranging from a wishlist to detailed product documentation.

3.1. List of Desired Features

The wish list comprises all criteria and specifications that the designed product must fulfill, beginning with incorporating all elements outlined in the Demands and Wishes [15]. The collection of various ideas, information, and unstructured data concerning the core problem-solving goals that a 3D printing machine must meet includes the following:

1. The 3D printing machine is user-friendly and easy to operate.
2. Components and materials are readily available on the market.
3. The design is simple and straightforward.
4. Assembly of the machine can be performed by a single person.

5. Maintenance and care of the machine are uncomplicated.
6. The machine is portable and easy to move.
7. It requires minimal space for operation.
8. The machine is capable of extruding filament from recycled plastic bottle waste

All obtained ideas, information, and data have been clearly defined and compiled into the specifications overview following Demand (D) or Wished (W) as per Table 1.

Table 1. Specifications overview of the 3D printing machine

Parameter	Specification	D/W
Dimension	Machine Length	D
	Machine Width	D
	Engine Height	D
Material	Aluminum Profile	D
	Acrylic	W
	Quality	D
	Available on the market	D
Mechanization	Good mechanical system	D
Production	Assembled using basic tools	D
	Cost-effective for assembly and maintenance	W
	Support for development and upgrades	W
Maintenance	Maintenance is simple and straingforward	D
	Designed for scheduled periodic maintenance	W
Safety	Durabke and rigid frame structure	D
	Equiped with a warning label	D
Ergonomics	Portable adoption	D
	User-fiendly	D

Once the list of desired features is defined, the next step involves functional decomposition 1 and 2 by breaking down the system requirements into their core functions by removing specific user wishes (W) to focus on fundamental needs. Design generalization 3 then further refines and broadens these core functions. From this process, the key design objectives are identified: a well-engineered mechanical system that is easy to assemble, maintain, and transport, while also being durable and user-friendly.

3.2. Function Structure

A function structure represents the interaction between a system's inputs and outputs as it performs a specific task, whereas the overall function refers to the tool's intended purpose or utility [16], [17]. The comprehensive function of a 3D printing machine can be represented through a block diagram, detailing the flow and interaction between system inputs and outputs to clarify operational dependencies, as shown in Figure 2.

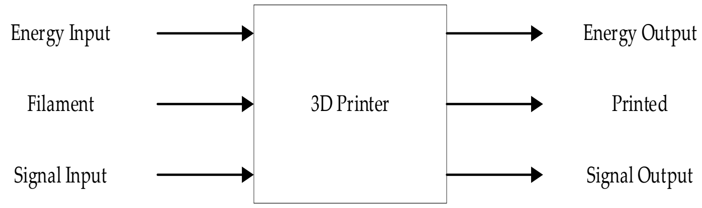


Figure 2. Functional block diagram

The overall function diagram may be further elucidated by delineating the various functional substructures, thereby providing a comprehensive understanding of how each component collaboratively contributes to the attainment of the system's overarching objective, as depicted in the Figure 3.

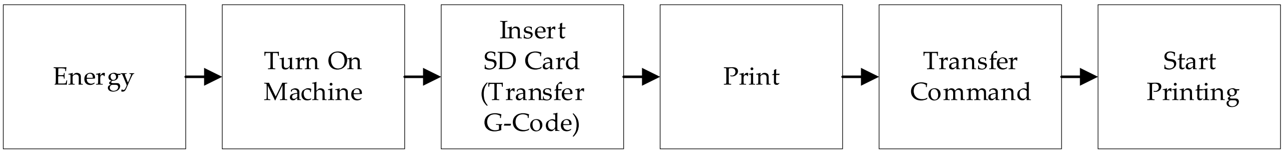
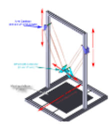
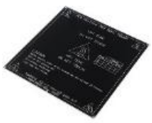


Figure 3. Functional substructure of the 3D Printer

3.3. Solution Principle

The combination method is an approach employed during the design process to generate potential solutions by systematically integrating various components into product configurations. This method facilitates the evaluation and comparison of multiple design variants, enabling the identification and selection of the most optimal solution based on predefined criteria [18]–[20]. Two distinct component variants are identified for integration in the 3D printing machine design, as shown in Table 2.

Table 2. Design principles for 3D printing machine solution

Description	**Principle Solution Variants**			**Information**
	1	**2**		
Machine Model			1	The Cartesian model is based on a straightforward concept, featuring three independent axes—X, Y, and Z—that operate independently to enable movement.
			2	The CoreXY model is comparatively more complex, employing two stepper motors that operate concurrently to control the movement of the nozzle.
Engine Frame			1	Aluminum profiles exhibit high structural strength and demonstrate strong resistance to pressure, vibration, and deformation.
			2	Acrylic exhibits low tolerance to significant pressure and vibration, particularly during high-speed machining operations
Power Transmissin System			1	The stepper motor is a critical component in 3D printing, responsible for precisely controlling the movement of the nozzle, print bed, and extrusion mechanism
Transmission System			1	V-slot rails are easy to install but tend to wear out quickly; however, they are generally more cost-effective
			2	Linear guides offer high precision and superior durability, although they come at a relatively higher cost
Extrusion			1	Single Gear Extruder: Features a simple design and is well-suited for printing standard filaments
			2	Double Gear Extruder: Provides stronger and more precise filament drive, enabling reliable printing with flexible filaments.
Hot End			1	PTFE Tube Hot End: Operates effectively within a temperature range of 240°C to 260°C, benefiting from PTFE's heat-insulating properties to withstand thermal stress.
			2	Full Metal Hot End: Supports higher operating temperatures up to 300°C, allowing compatibility with a wider variety of filament types
Heated Bed			1	Heated Bed: Heats and maintains the print bed temperature to ensure optimal adhesion of the first printed layer.

Description	Principle Solution Variants 1	2		Information
Controller Board			1	RAMPS: A modular control board system that requires user assembly and configuration of multiple components.
			2	Creality V4.2.2: An integrated control board that consolidates various functions, minimizing the need for extensive user setup and configuration.

3.4. Module Structure

At this stage, a functional structure is developed to explore alternative component combinations, followed by an evaluation and selection process to identify the most suitable solution [21], [22]. An alternative configuration of the selected solution principles for the 3D printing machine design is outlined in the following Table 3.

Table 3. Integrated solution principle variants

Division of Functions	Principle Solution Variants 1	2
Machine Model		
Engine Frame		
Drive System		
Transmission System		
Extrusion		
Hot End		
Heated Bed		
Controller Board		

Note. Variant 1: 1.1 – 2.1 – 3.1 – 4.1 – 5.2 – 6.2 – 7.1 – 8.2
Variant 2: 1.2 – 2.2 – 3.1 – 4.2 – 5.1 – 6.1 – 7.1 – 8.1

Designing a tool typically begins with exploring several conceptual alternatives, followed by selecting the most effective one for development [23], [24]. This aids decision-making by showing how each option satisfies the criteria, as shown in Table 4.

Table 4. Solution Variant Decision-Making

Solution Variant Selection	
Selection Criteria	**Decision**
+ (Yes)	+ (Solution sought)
- (No)	- (Remove solution)
? (Lack of Information)	? (Gather information)
! (Check Specifications)	! (See specifications)

A: According to functional needs.
B: According to the wish list.
C: In principle it can be realized.
D: Within the limits of production costs.
E: Understanding of the concept.
F: As expected.
G: Meet the requirements.

Principle Solution	A	B	C	D	E	F	G	Information	Decision
V1	+	+	+	+	+	+	+	In accordance	+
V2	+	+	+	+	?	-	+	It is not in accordance with	!

Between the two alternative combinations of solution principles considered, variant 1 was selected as the most suitable option.

3.5. Initial Level Design

Once the solution principle is defined and the solution variant selected, the initial form of the 3D printing machine design can be developed, as shown in Figure 4.

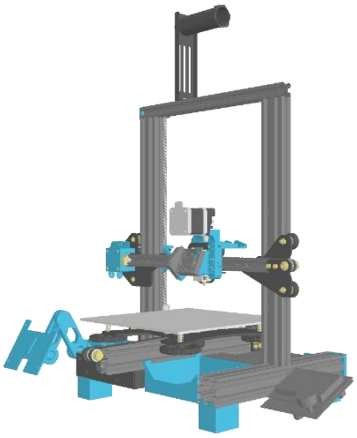


Figure 4. Initial design of 3D printing machine

3.6. Design Details

A Bill of Materials (BoM) documents the components of a product, with data relevant to its structural integrity and quality standards [25], which documents every change in form, enabling efficient raw material demand calculation and movement tracking [26]–[28]. Table 5 details the Bill of Materials, covering all assembly and design criteria for the 3D printing machine as specified.

Table 5. BOM for 3D Printing Machine

Description	Qty.	Price /Unit	Total price	Description	Qty.	Price /Unit	Total price
eSUN Mint Green	1	230,000	230,000	Bearing 608Z	1	8,000	8,000
eSUN Deep Black	1	230,000	230,000	Hot End Kit	1	80,000	80,000
Aluminum Profile 2020	1	75,000	75,000	DC Fan 4010	2	9,000	18,000
Aluminum Profile 2040	1	170,000	170,000	Blower Fan 4010	1	14,000	14,000
Aluminum Profile 4040	1	160,000	160,000	Extruder Bracket (Printed)	1	15,000	15,000
Spool Holder Bracket (Printed)	1	4,000	4,000	NEMA 17 Stepper Motor	4	135,000	540,000
Spool Holder	1	20,000	20,000	Limit Switch	3	20,000	60,000
Frame Dumper (Printed)	4	8,000	32,000	GT2 Timing Pulley	2	10,000	20,000
X Axis Bracket	1	80,000	80,000	Timing Belt	2	25,000	50,000
X Axis Motor Bracket (Printed)	1	16,000	16,000	Flexible Shaft Coupling	1	10,000	10,000
X Axis Tensioner	1	15,000	15,000	M8 Threaded Rod	1	60,000	60,000
Backplate Mounting Slider	1	15,000	15,000	Electrical Case	1	30,000	30,000
Y Axis Motor Bracket	1	25,000	25,000	Electrical Cover (Printed)	1	30,000	30,000
Y Axis Endstrop Bracket	1	10,000	10,000	Controller Board	1	850,000	850,000
Y Axis Tensioner	1	15,000	15,000	PSU 24V 15A	1	250,000	250,000
Bed Base Plate Slider	1	50,000	50,000	PSU Holder (Printed)	1	60,000	60,000
Heated Bed	1	170,000	170,000	LCD Display Screen 12864	1	120,000	120,000
Glass Bed	1	30,000	30,000	LCD Case (Printed)	1	25,000	25,000
Z Axis Motor Bracket	1	15,000	15,000	LCD Holder (Printed)	1	30,000	30,000
Z Axis Endstop Bracket	1	15,000	15,000	**Total**			**3,657,000**
Z Axis Holder (Printed)	1	10,000	10,000				

The production of a single 3D printing machine takes approximately 200 minutes, with labor costs amounting to Rp 333.33 per minute. The total labor cost calculation is as follows:

$$Wage/Minute \times Production\ Time = 333.33 \times 200 = 66{,}66 \quad (1)$$

The overall cost required to manufacture the 3D printing machine is Rp 3,723,000.00. Overhead costs are not specifically broken down in this process. The specifications of the machine, which will be used to process filaments from recycled plastic bottles, are detailed in Table 6.

Table 6. Specification 3D Design Machine

Specification	Detail
Framework	Aluminum Profile
Model	Cartesian
Dimensions	475*400*495mm
Work Area	235*235*300mm
Heavy	7Kg
Motor	NEMA 17
Extrusion	Direct
Max Temp. Nozzle	0 - 270°C
Max Temp. Bed	0 - 110°C
Nozzle Diameter	0.4mm
Filament Diameter	1.75mm
Firmware	Marlin 2.1.2.4

4. DISCUSSION

The properties of filaments derived from plastic bottles differ somewhat from those of market-standard filaments. Consequently, processing these materials necessitates a 3D printing machine designed to adapt to these characteristics, which include:

1. Filaments tend to crystallize easily
2. Required high nozzle temperatures
3. Contain voids or gaps
4. Exhibit inconsistent diameters

These filament characteristics frequently result in suboptimal print quality due to problems such as clogging, jamming, under-extrusion, and heat creep. Variant 1 employs a Cartesian kinematic model, which is widely adopted due to its straightforward mechanical design and ease of understanding. In contrast, Variant 2 utilizes the CoreXY mechanism, where the X and Y axes collaborate to position the nozzle. Furthermore, the Cartesian configuration involves fewer and less complex components, contributing to reduced manufacturing costs.

The extrusion system of the 3D printing machine utilizes a Dual Gear Extruder and a Full Metal Hot End to accommodate the properties of filaments made from PET plastic bottle waste (identified as code 1), which have a melting point between 260°C and 265°C. Using a Hot End with a PTFE tube is less effective in this context, as PTFE tubes are recommended for temperatures below 260°C. The porous nature of the plastic bottle filament prevents effective retraction—the process of pulling back filament during printing—which is addressed by employing a Dual Gear Extruder that offers more precise and reliable filament extrusion across various filament types. The choice of Aluminum Profile for the frame is intended to facilitate the development of advanced 3D printing models, particularly for users with a deeper understanding of the CoreXY kinematics. While Acrylic components can reduce manufacturing costs, Aluminum Profiles provide superior durability and structural integrity.

5. CONCLUSION

This study contributes to the advancement of sustainable manufacturing by introducing a systematically designed 3D printer that is capable of utilizing recycled PET bottle waste as filament. The novelty of this research lies in the integration of the VDI 2221 design methodology into the development of a low-cost, user-friendly 3D printer optimized for processing non-standard filament materials produced via pultrusion. Unlike conventional 3D printers, this machine is tailored to accommodate the inconsistent thermal and physical properties of recycled plastic filament by employing a full-metal hot end and dual-gear extruder capable of reaching up to 270°C.

Through a structured design process, two design variants were developed and evaluated, with Variant 1—featuring a Cartesian kinematic model—selected for its functional performance, ease of assembly, and cost-efficiency. The final prototype offers key specifications that meet the design objectives, including a maximum nozzle temperature of 270°C, a heated bed up to 80°C, and a total production cost of approximately IDR 3,657,000.

The results demonstrate practical benefits for users and the broader industry by supporting the reuse of plastic waste, reducing environmental impact, and providing an affordable alternative for small-scale production. Future research is recommended to evaluate the print quality using different types of recycled filaments and to further optimize machine components for better performance, accuracy, and long-term reliability.

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