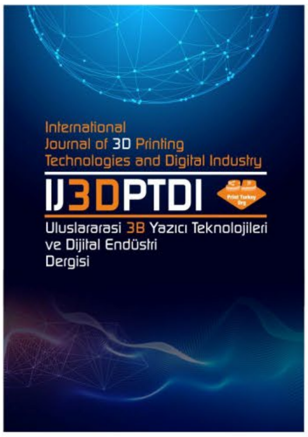

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CONCEPT DESIGN FOR OPTIMIZING MASS PRODUCTION PROCESSES WITH 3D PRINTER IN THE INDUSTRY

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ABSTRACT

This study deals with the conceptual design of three-dimensional (3D) printer technology for process optimization in industrial production. While initially 3D printers were primarily used for rapid prototyping, advancements in technology have transformed them into a new technology for mass production. Within the scope of this study, firstly, investigations were conducted on how Industry 4.0 technologies (internet of things (IoT), smart factories) are utilized on the production line. The first-in, first-out (FIFO) method, which is used in communication between objects (3D printer, industrial robot arm, conveyor belt, and assembly unit), has been elaborated in detail. The aim of this study is to comprehensively address and convey how Industry 4.0 technologies increase production speed and efficiency in mass production processes through the created conceptual design. In the obtained conceptual design, even though the production line has been kept limited, every stage of the production process has been thoroughly explained and examined from start to finish. Within the scope of the study, sample data of the production stages are presented with the sample software called 3D Production and Automation Software (3D MAS), which was developed using the C# programming language on Microsoft Visual Studio Community 2022 IDE. In the next study, efforts can be directed towards expanding the limited production line presented in this work, introducing other Industry 4.0 technologies, and incorporating them into the conceptual design of the production process.

Keywords: 3D Printer, Internet of Things (IoT), Concept Design, Industry 4.0, Smart Factories.

1. INTRODUCTION

Three-dimensional (3D) printers operate on the principle of additive manufacturing, where objects are created by adding layers, utilizing various materials such as metal, plastic, composites, and organics, based on digital data. The 3D printing technology, first emerged in the 1980s with Stereolithography (SL) technology developed by the company 3D Systems. During that time, various layering manufacturing methods were developed, leading to patent applications. Subsequently, these developed technologies were commercialized by the respective companies. Following SL, in the early 1990s, various other 3D printing methods were developed and brought to the commercial market by different companies. These methods include Laminated Object Manufacturing (LOM) by Helysis, Fused Deposition Modeling (FDM) by Stratasys, Selective Laser Sintering (SLS) by DTM, Direct Metal Laser Sintering (DMLS) by EOS, Solid Ground Curing (SGC) by Cubital, and Three Dimensional Printing (3BP) by Soligen [1]. Figure 1 displays visuals related to some of the 3D printing technologies.

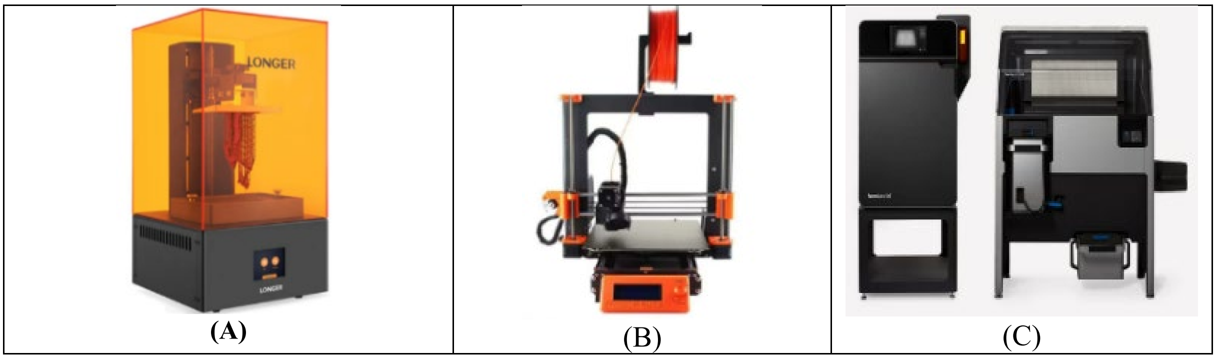


Figure 1. Three-dimensional printing technologies (A: SL, B: FDM, C: SLS).

The SLS (Selective Laser Sintering) technology is fundamentally based on the principle of melting powdered material using a carbon dioxide laser beam. In practice, the material is first heated to its melting point. Then, a laser beam fuses the powdered materials at specific positions for each layer as specified in the design. [2]. The SL (Stereolithography) method is based on the principle of photopolymerization of photosensitive resin materials when exposed to UV light. The SLA manufacturing method consists of a resin bath, a laser source with specialized hardware and software, and a platform used for the immersion process into the resin bath. After scanning the resin surface with a laser beam, the first layer is created. Then, the platform is submerged again into the resin bath at a distance equal to the layer thickness, and another layer is formed, connecting to the previous one [3]. In LOM (Laminated Object Manufacturing) technology, materials are cut into layers using a mechanical cutter and laser, then they are brought together using a lamination method. Pre-shaped layers can be used in lamination, or the printing model can be shaped after the process [4]. The SGC (Solid Ground Curing) method is based on photosensitive polymer and employs a powerful UV lamp or laser source to create the geometry of each layer [3-5]. In the 3BP (Three Dimensional Printing) method, a powder-based material is deposited layer by layer onto the printing surface. Then, a liquid adhesive delivered onto the powder particles through an inkjet print head allows the particles to come together, thereby forming the layers corresponding to the part geometry [6].

The FDM (Fused Deposition Modeling) technology is a method among additive manufacturing techniques that was developed in the 1980s and it is widely used by many industries [7]. In this technology, a filament made of thermoplastic material is used. This filament is wound onto a spool in wire form, then a drive gear turns and moves the filament towards a heated chamber, where it melts. As a result, the molten filament is conveyed from the nozzle tip in the print head to the print bed. According to the gcode information obtained based on the CAD file of the print model and the slicing program, the print head moves. This allows the molten filament to create the layers and produce the 3D printed model. Figure 2 a schematic diagram shows the working principle of FDM 3D printers.

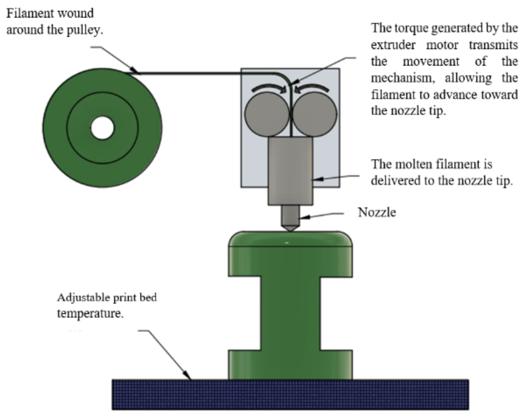


Figure 2. Schematic diagram of an FDM 3D printer.

FDM 3D printers are categorized into four different types: Cartesian, polar, delta, and robotic arm, based on structural configuration changes. In Cartesian FDM 3D printers, linear connections enable movement along the x, y, and z axes. The print bed can move along the z-axis, while the print head can move along the x and y axes. Various configurations are available where the print bed can move along the y-axis, while the print head moves along the x and z axes. In Polar FDM printers, while the print head moves linearly along the x and y axes, the print bed rotates around the z-axis. Delta FDM 3D printers have three arms on the print head that can move in all directions. In robotic-arm-based FDM 3D printers, the print head is located at the end of a robotic arm. The position and orientation of the print head are determined by the configuration of the robotic arm [8]. Figure 3 illustrates the classification of different types of FDM 3D printers.

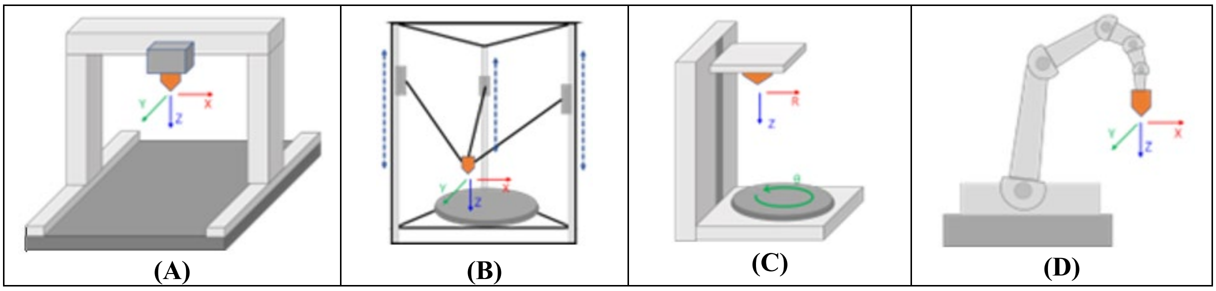


Figure 3. Classification of FDM-type printers (A: Cartesian, B: Delta, C: Polar, D: Robotic Arm) [9].

The principle of layer-by-layer manufacturing, which is the production principle of 3D printers, is the reverse of subtractive manufacturing. In CNC turning and milling machines, parts are cut and removed from a material block by the method of removing chips to obtain the final product. In the layer-by-layer manufacturing method, the designed 3D object is obtained by combining the material layers successively created by the printer. This eliminates the waste materials generated in subtractive manufacturing methods and prevents material losses. In this way, the same final product is obtained using less material. Figure 4 shows images of sample prints obtained using 3D printing technology.

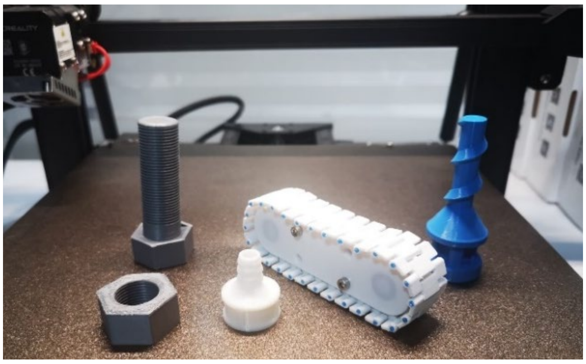


Figure 4. Sample prints obtained using 3D printing technology.

Additionally, due to the manufacturing method, 3D printing eliminates the need for mold design and production that might be required in traditional methods, as the digital data of the product is used to create the 3D print. The reduction in material waste, the elimination of additional production stages such as mold design and production, and the ability to start production immediately after the design are some of the reasons why 3D printing technology is preferred. Additionally, it allows incoming orders to be sent to the 3D printer, and production can take place rapidly without the need for any molds or assembly lines.

The ability to change the production line without the need for additional processes like tool changes or mold design, which are typically required in traditional manufacturing methods, enhances the efficiency and cost-effectiveness of 3D printer technologies in terms of time and cost. Furthermore, it provides another advantage by enabling cloud-based production, which is one of the Industry 4.0 technologies. When we consider 3D printers within the scope of Industry 4.0 technologies, it becomes evident that they hold a significant place in Industry 4.0, especially when combined with technologies such as cloud technology, the internet of things (IoT), sensors, wireless communication, and industrial robot arms [1]. While 3D printing technologies offer many advantages, the strength of the print depends on the print settings. Therefore, to achieve the desired strength values for the final product, the print parameters need to be appropriately adjusted [10]. Figure 5 illustrates the stages of product formation in 3D printers.

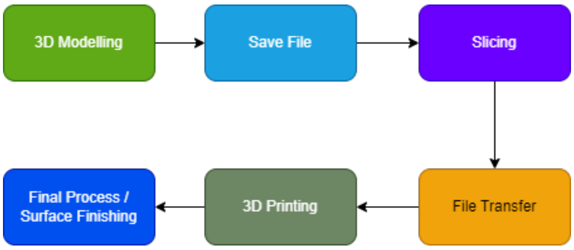


Figure 5. 3D printer product creation stages [1].

1.1. Development of Industrial Revolutions and Industry 4.0

Throughout history, there have been three Industrial Revolutions in industry. The First Industrial Revolution (Industry 1.0) began with the invention of the steam engine in the 18th century, aiming to increase production. Industry 2.0, at the beginning of the 20th century, facilitated the transition to mass production by using electrical energy. Industry 3.0 marked a period when production systems in industry shifted from analog to digital systems. Through these developments, the first three Industrial Revolutions introduced mechanization, electricity, and information technology (IT) into human production processes to enhance productivity. However, merely increasing efficiency was not sufficient for companies to stand out in global competition. Companies have needed innovative approaches that allow information transfer throughout the entire lifecycle from production to supply, along with the rapid adaptation of virtual and physical structures. This has become essential for them to excel. With the removal of trade barriers between countries following the end of the Cold War, commercial exchanges among these countries have increased. In the 2000s, changing customer expectations for products have led to greater complexity in companies' production methods. In this context, the need for interdisciplinary collaboration by companies has led to the emergence of Industry 4.0, where objects communicate and interact over the internet, as a response. The development of industrial revolutions is illustrated in Figure 6 [11].

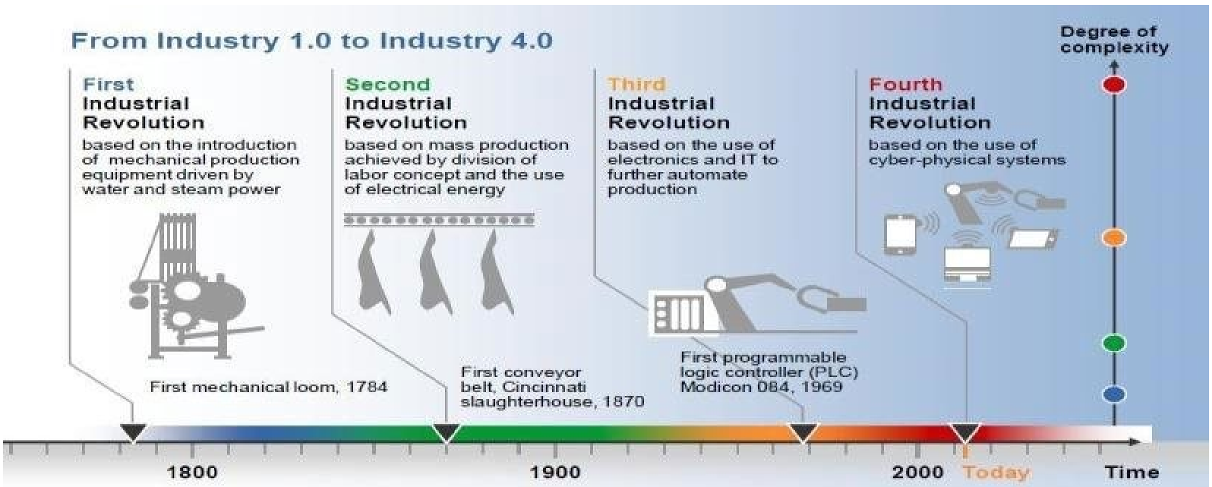


Figure 6. The progression of industrial revolutions [11].

The structure of Industry 4.0 is fundamentally altering the dynamics of production and consumption. This new approach, characterized by production systems that adapt to changing consumer needs, has brought about automation systems that communicate and coordinate continuously with each other. As a result, it encourages close collaboration among various disciplines in the product development phase [12].

Table 1. Structure of Industry 4.0 [13].

Field	Sector	Applications
Technologies	Core Technologies	Internet of Things, Artificial Intelligence, Cloud Systems, Big Data, Robots, and 5G Communication
	Base Technologies	Data Security, Sensors, New Materials, Genomic Technologies
Applications	Products	Wearable, Synthetic, and Biological Products.
	Smart Systems	Smart Cars, Smart Factories, Smart Security Systems, Smart Defense Systems, Smart Energy Systems
Institutions	Legal Framework	Data Regulations, Testing and Certification, Guidelines for Smart Applications

In Table 1, it is stated that the structure of Industry 4.0 consists of three elements: technologies, applications, and supporting institutions, and that these elements can change according to the expectations of stakeholders. [13-14]. In this context, the technologies involved in the 4th Industrial Revolution are divided into core and base technologies. Additionally, applications, products, and smart systems are considered, and supporting institutions are also part of this structure [14-15].

1.2. Industry 4.0 Technologies

Many of the highly developed countries have invested in obtaining advanced mass production systems rather than conventional production. The majority of this investment has been made to create smart factories using 4th Industrial Revolution technologies. For example, in the first dark factory known as a smart factory in operation in China, mobile phone modules are produced using "smart" technologies where objects communicate with each other, and the use of human labor has been eliminated. As a result, the number of workers has been reduced by 90%, and the defect rate has dropped from 25% to 5%. The structures that enable objects to communicate and interact with each other are referred to as the IoT. From a technical perspective, IoT encompasses physical entities that include embedded systems, along with electrical, mechanical, computer, and communication mechanisms, enabling internet-based communication and data exchange. Some examples of industrial IoT applications are shown in Figure 7 [12].

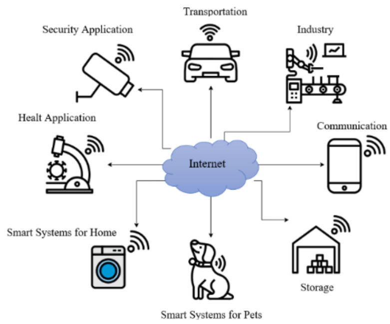


Figure 7. Use cases of the Internet of Things (IoT) [12].

Cloud-based Manufacturing (CBM), another Industry 4.0 technology, allows for increased efficiency, reduced product costs, and optimized raw material procurement to meet changing customer demands. Based on a network-connected production model, reconfigurable cyber-physical production lines can be created on-demand. The benefits provided by this technology include scalability, accessibility from anywhere, and virtualization. [12].

1.3. Omnidirectional Cellular Conveyor

Conventional conveyor belts allow objects to move only in a straight line. In order for the object to perform turning, sorting, and singulation movements, the conveyor belt system requires the addition of mechanical components and modules.

An omnidirectional cellular conveyor, unlike a traditional conveyor, can move materials in any direction. They are widely used in various industries, including manufacturing, logistics, and packaging. These conveyors feature small individual cells or compartments that provide greater flexibility and precision in material handling. The movement of objects in different directions is controlled solely by software. Changes in the control software alter the material flow task [16]. In Figure 8, the trajectory of objects on an omnidirectional cellular conveyor is depicted [17].

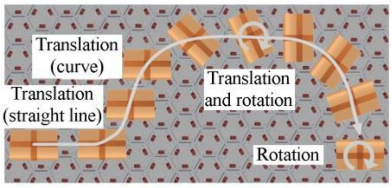


Figure 8. The trajectory of objects on an omnidirectional cellular conveyor [17].

2. LITERATURE REVIEW

In the literature, there are studies related to process optimization in mass production. For example, Doğan and Takcı (2015) conducted a process improvement study using simulation in a textile company. The study was conducted in a textile factory located in the Kayseri province. In this study, the aim was to efficiently utilize resources such as materials and equipment to achieve the desired capacity [18]. Aljinović et al. (2022) conducted a study aimed at optimizing and improving the assembly line of manually produced gearbox production through the utilization of Industry 4.0 technologies [19]. Gül and Toptaş (2021) conducted a study on the optimization and effects of automation systems in the design processes. In the study, the effects of physical and parametric changes on the production process were investigated through an automation line that caps bottles of different sizes. The example production system they designed resulted in a 30% improvement in cycle time and design time in the production process [20]. Herbuś and Ociepka (2017) utilized the mechatronic concept designer module of PLM Siemens NX to perform virtual commissioning in a production line. Their work aimed at achieving cost and time efficiency in the commissioning process and reducing time-to-market [21]. In Parlar's (2022) study, a concept design was developed for a specialized machine that transports spherical materials resembling balls from one hopper to another at a specified distance. The research introduced the possibility of conveying granular materials not only through mechanical methods such as belts, screws, and buckets but also utilizing pneumatic and hydraulic systems. [22].

When considering commercially available products, the Creality CR-30 3D PrintMill, depicted in Figure 9, is the first 3D printer designed theoretically for infinite-length printing and batch production [23]. With the capability of continuous infinite printing, it offers time and cost savings. Completed prints advance on a heated conveyor belt and detach automatically from the belt. Therefore, there's no need to clean and restart the print bed every time.

Figure 9. Creality CR-30 3D PrintMill conveyor 3D printer [23].

3. MATERIAL VE METHOD

In this study, a conceptual design for 3D printer technology in mass production process optimization has been realized. The design was completed using the computer software Autodesk Fusion360, which is a 3D solid modeling program with a free individual educational license. When positioning the 3D printers on the factory production line, it was considered that they should be advantageous for mass production. Furthermore, during the expansion of the production line, it was planned to have the maximum number of 3D printers and an adequate number of robotic arms that would fit within the unit area. Industrial robotic arms were placed on the production line to transfer the products produced by 3D printers onto the conveyor belt. During the placement of industrial robotic arms, ensuring access to the prints produced by 3D printers around the robotic arm was taken into consideration. As the completed prints needed to be directed to different assembly units, the number of conveyor belts on the production line was increased. Prints produced by 3D printers are initially picked up by the robotic arm and placed on the omnidirectional cellular conveyor belt. From the omnidirectional cellular belt, they are transferred to the conveyor belt of the respective assembly unit. An algorithm was created to meet the design requirements, and the details are shown in Figure 10.

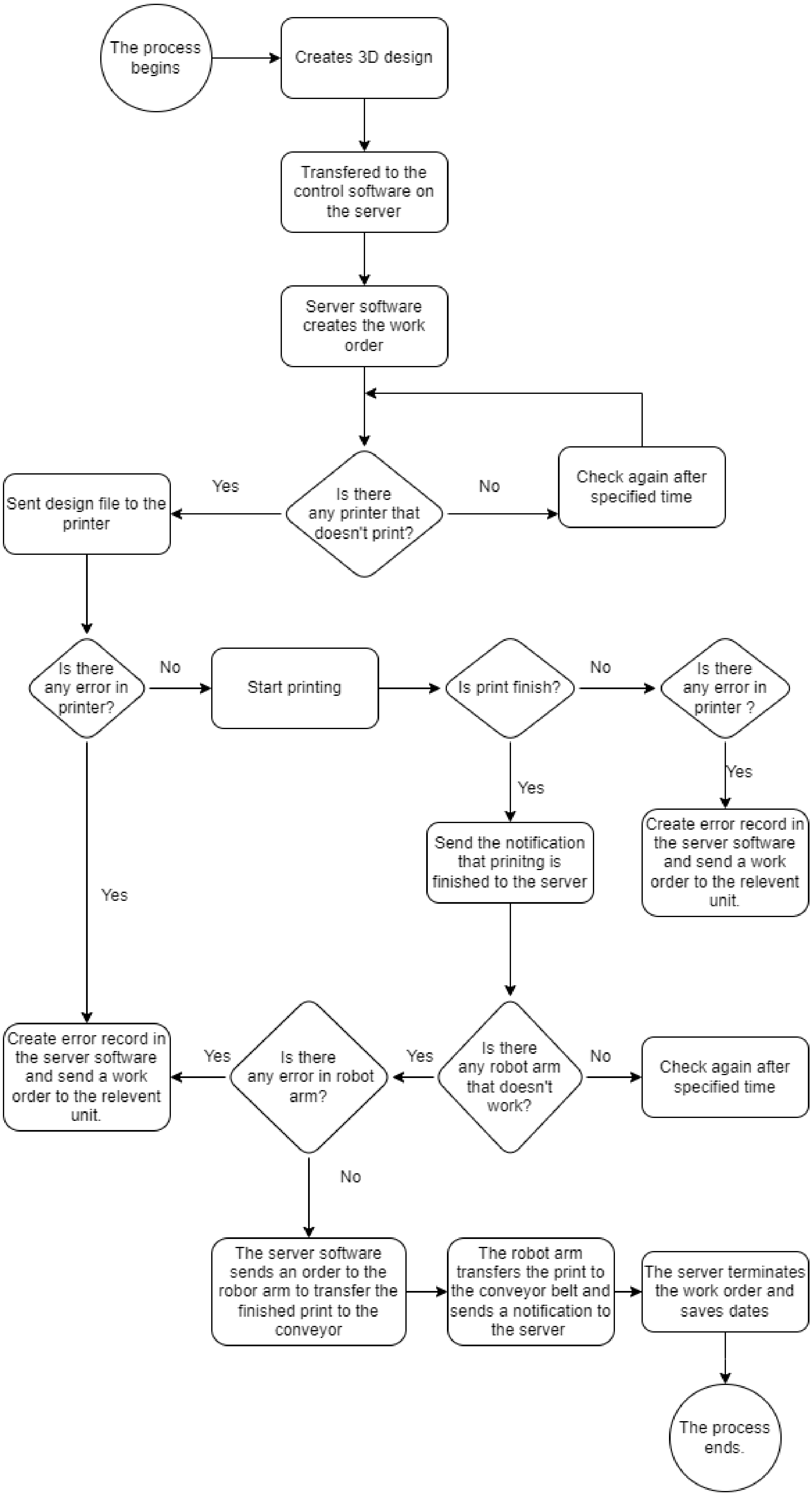


Figure 10. Algorithm Created to Meet Design Requirements.

The workflow in the conceptual factory design is as follows: Firstly, the three-dimensional design and slicing processes of the customer's request are carried out by the product development unit. The created work piece is then added to the production queue. According to the First in, First Out (FIFO) method, task assignment signals are sent to the 3D printers via IoT modules. The server transmits the print start signal to the available 3D printer according to the FIFO method. Once the printing process begins, the printer sends a "in progress" signal to the server. The server records this information in the database. In the event of an error (such as filament sensor failure, heat bed sensor is failure, stepper motor failure, level calibration error, robotic arm motion sensor error, electrical issue, filament depletion, out of filament (filament finished), filament replacement, nozzle clogging, layer defects, nozzle overheating, mainboard overheating, fan failure, connection error, sticking error, camera error and support error), error message codes are transmitted from the 3D printer to the server along with an "error" signal. In addition, if there is a need for a change in filament type during printing, the corresponding error code is generated, and a work order is sent to the relevant department. In the event of a filament change or the occurrence of any of the errors mentioned above, the server automatically generates a work order, communicates the error code to the maintenance department, and disables the respective printer. In the database, the printer status, which was previously marked as "in progress," is updated to "error," and the relevant error code is added. The server reassigns the unfinished job to another "available" printer. Once printing starts without errors, the 3D printer sends the "in progress" signal to the server. During printing, at intervals specified by the operator, photo and video data are transferred to the server, and potential print errors unrelated to the printer are analyzed. In case of any printing error, information is sent to the server and the operator, along with the error code. When the printing process is completed, relevant data about the print (such as printing time, filament usage, location information, photos, videos, etc.) is transmitted to the server, and this data is recorded in the completed jobs table. After the server records the data, the job status on the printer is updated to "done." When the design is sent to the printer, concurrently, if support material is expected to form on the printed model, a work order is dispatched to the relevant department for the removal of supports. Following the completion of the print transportation process with the robot arm, the printer's operational status is updated to "available." Once the printer's job status is "done," the ID or location information signals of the completed task are transmitted from the server to the robotic arm. The robotic arm picks up the print from the printer's bed and initiates the transfer process to the multi-cellular conveyor belt. In the event of any errors, similar to the 3D printer, error signals are transmitted to the server and the malfunction unit. The server transmits the information of the 3D printer in the "done" status to the available robot arm. The robot arm takes the print and transfers it to the multi-cellular conveyor belt. The multi-cellular conveyor belt transfers the print to the conveyor belt of the unit defined in the job order.

The interface of the sample software called 3D Manufacturing and Automation Software (3D MAS), developed using the C# programming language in Microsoft Visual Studio Community 2022 IDE within the scope of the study, is shown in Figure 11.

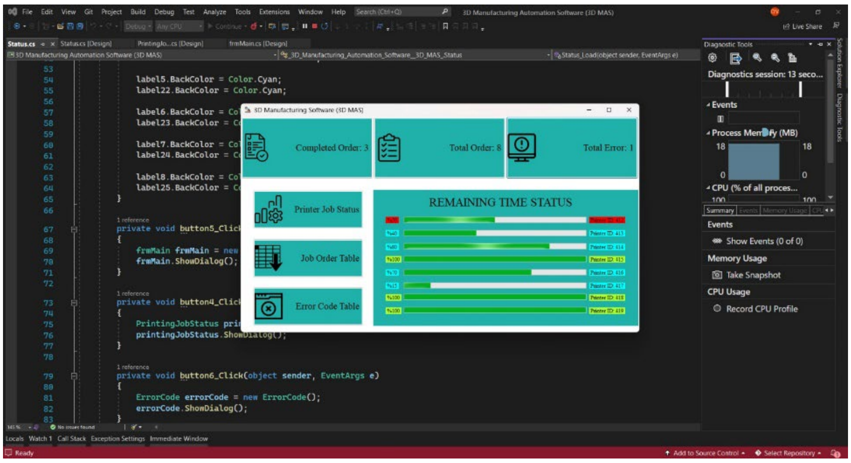
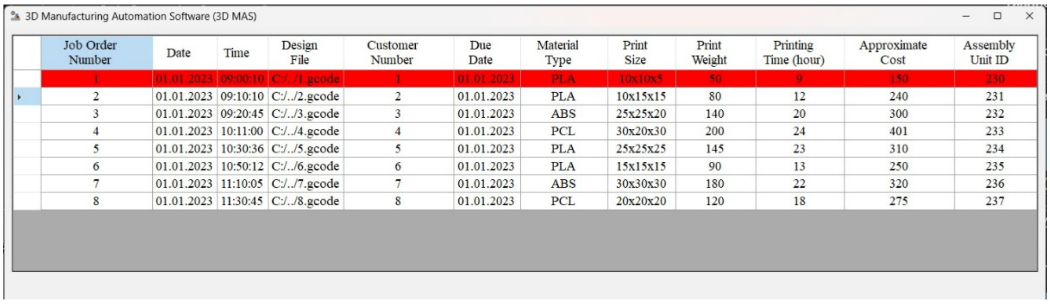


Figure 11. 3D Manufacturing and Automation software interface (3D MAS).

The operator can instantly view completed orders, the total number of orders, and the number of errors in real-time. Access to the real-time status information of job orders can be obtained through the 'Printer Job Status' button. The table displayed in the window that opens when the button is clicked is shown in Figure 12.


3D Manufacturing Automation Software (3D MAS)

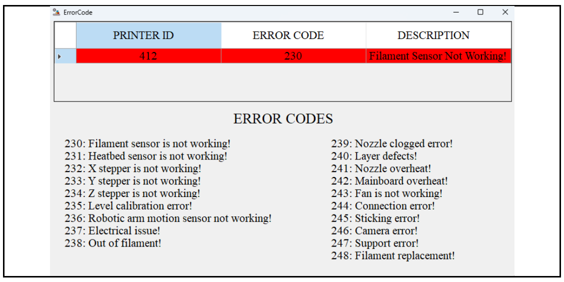
Job Order Number	Date	Time	Design File	Customer Number	Due Date	Material Type	Print Size	Print Weight	Printing Time (hour)	Approximate Cost	Assembly Unit ID
1	01.01.2023	09:00:10	C:/../1.gcode	1	01.01.2023	PLA	10x10x5	50	9	150	230
2	01.01.2023	09:10:10	C:/../2.gcode	2	01.01.2023	PLA	10x15x15	80	12	240	231
3	01.01.2023	09:20:45	C:/../3.gcode	3	01.01.2023	ABS	25x25x20	140	20	300	232
4	01.01.2023	10:11:00	C:/../4.gcode	4	01.01.2023	PCL	30x20x30	200	24	401	233
5	01.01.2023	10:30:36	C:/../5.gcode	5	01.01.2023	PLA	25x25x25	145	23	310	234
6	01.01.2023	10:50:12	C:/../6.gcode	6	01.01.2023	PLA	15x15x15	90	13	250	235
7	01.01.2023	11:10:05	C:/../7.gcode	7	01.01.2023	ABS	30x30x30	180	22	320	236
8	01.01.2023	11:30:45	C:/../8.gcode	8	01.01.2023	PCL	20x20x20	120	18	275	237

Figure 12. Printer Job Status.

The Remaining Time Status graph allows you to see the time printers spend during printing and the time required to complete the printing. In the event of a possible error in the printer, the printer ID information will be displayed in red. Figure 13 shows an image of the graphic.

Figure 13. Remaining Time Status Graph.

The "Error Code Table" button on the interface allows access to detailed information in the event of an error. In case of an error, the error code and description for the respective job order number are recorded in the sample error code table shown in Figure 14.


ErrorCode

PRINTER ID	ERROR CODE	DESCRIPTION
412	230	Filament Sensor Not Working!

ERROR CODES

230: Filament sensor is not working!
231: Heatbed sensor is not working!
232: X stepper is not working!
233: Y stepper is not working!
234: Z stepper is not working!
235: Level calibration error!
236: Robotic arm motion sensor not working!
237: Electrical issue!
238: Out of filament!
239: Nozzle clogged error!
240: Layer defects!
241: Nozzle overheat!
242: Mainboard overheat!
243: Fan is not working!
244: Connection error!
245: Sticking error!
246: Camera error!
247: Support error!
248: Filament replacement!

Figure 14. Error Code Table.

4. RESULTS

In this study, a conceptual design aimed at process optimization in mass production using 3D printing technology was executed in Autodesk Fusion360, a computer software with a free individual educational license for 3D solid modeling. The proposed 3D MAS software in this study was developed using the object-oriented programming language C# within the Microsoft Visual Studio Community 2022 environment. However, if needed, it can be developed with languages such as Java, Python, C++, Swift. Additionally, it can be designed as a web-based application. Microsoft SQL Server database was utilized for storing application data and generating reports. Alternatively, MySQL, PostgreSQL, or Oracle databases can be used if required. The proposed system is designed to facilitate continuous mass production with the capability of immediate intervention in case of errors. This minimizes time and labor losses, consequently leading to a reduction in unit costs. When designing the placement of 3D printers, the honeycomb design of beehives was taken into consideration. The advantage of positioning in hexagonal sections is to partition an area in the most efficient way possible [24]. As a result, the aim was to utilize the space of a production facility in the most efficient manner. Figure 15 illustrates the designed production line, with the fundamental components of the production line being numbered.

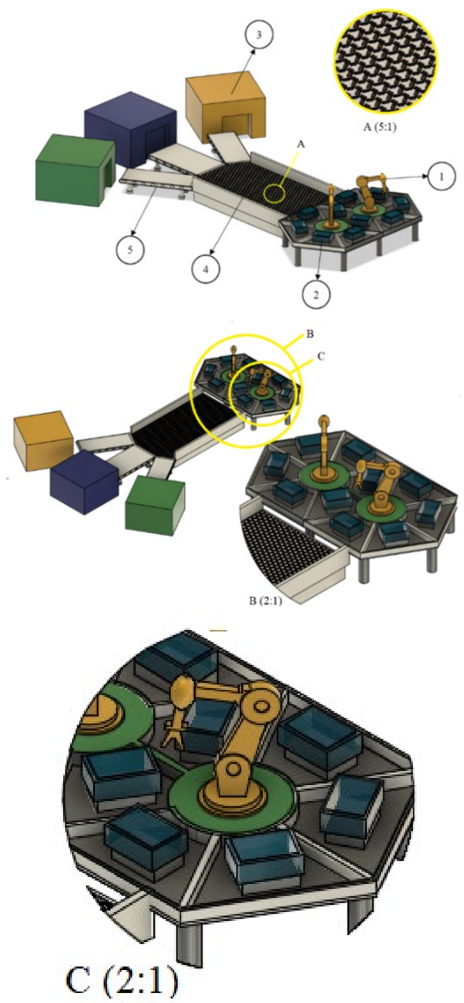


Figure 15. The Designed Production Line.

Corresponding expressions for these numbers are provided in Table 2.

Table 2. Components of a Production Line.

Number	Description
1	Industrial Robotic Arm
2	3D Printer
3	Assembly Unit
4	Omnidirectional Cellular Conveyor Belt
5	Conveyor Belt

5. CONCLUSION

This study deals with the conceptual design for process optimization in mass production using 3D printing technology, which is set to revolutionize manufacturing methods in the industry with the advancement of technology.

When examining the literature, it is observed that 3D printers are widely used in various fields. However, examples where printers are used within an automation system and production processes are automated are limited. This study focuses on the designs of 3D printers that are integrated with each other and utilize Industry 4.0 technologies. Industrial robot arms and versatile cellular conveyor belts have been employed in the production stages. Through a central computer software, all processes can be monitored, and real-time tasks can be defined. Additionally, maintenance and repair mechanisms have been incorporated into the system for potential errors. This highlights the uniqueness of the proposed system. The creation of the conceptual model, the transfer of the obtained prints to a versatile cellular conveyor belt, and their transfer to relevant units are all considered with the integration of Industry 4.0 technologies such as IoT, cloud-based communication, and smart factory approaches to ensure the most functional continuation of the process. Additionally, this study enables faster and more functional production with the conceptual design model obtained using 3D printers in the industry.

In future studies, it is expected that research and conceptual designs aimed at improving the efficiency of 3D printers in mass production will be conducted. These studies are expected to involve analyses in various simulation software to obtain detailed data. It is expected that, as a result of these simulated and data-driven studies, more efficient and high-performance production facilities will be established.

Furthermore, machines that perform subtractive manufacturing alongside or in conjunction with 3D printers can also be integrated, and additional enhancements can be made to the conceptual design.

In this study, the emphasis has been placed on the conceptual design utilizing identical 3D printers. In our subsequent research, we plan to develop an approach incorporating different types of 3D printers, where an appropriate printer is automatically selected by a deep learning-based control software. This will enable the system to make the selection of the most suitable printer and filament type based on design parameters.

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