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Amaresh Chakrabarti
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Industry 4.0 and Advanced Manufacturing

Proceedings of I-4AM 2022

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Preface

Industry 4.0 is about using connected intelligence to usher in greater productivity, quality, flexibility, safety and resource utilisation across manufacturing enterprises, in which advanced manufacturing such as Robotics or Additive Manufacturing plays a critical role.

The collection of papers in this book volume constitutes the Proceedings of the Second International Conference on Industry 4.0 and Advanced Manufacturing (I-4AM 22) held online at the Indian Institute of Science, Bangalore, India, during 10–11 January 2022. I-4AM 22 is the second in a series of biennial conferences held in India to bring together all stakeholders in manufacturing and Industry 4.0, in particular, those in academia and industry in both India and abroad, for them to deliberate on the nature, needs, challenges, opportunities, problems and solutions in this transformational area of endeavour.

I-4AM 22 was hosted online in Bangalore, the "silicon plateau" of the world, with the second fastest-growing community of start-ups, many of which are exploring emerging technologies such as IoT, IIoT, digital twins, sensor networks, I4.0 and so on to design new products, systems and services. The theme for I-4AM 22 was aligned with this ambiance. A specific focus of this conference is to provide a platform for exploring avenues for creating a vision of, and enablers for sustainable, affordable and human-centric Industry 4.0 and to showcase cutting-edge practice, research and educational innovation in this crucial and rapidly evolving area.

Seventy-Seven full papers were submitted, which were reviewed by experts from the I-4AM 2022 International Programme Committee comprising 75 members from 13 countries spanning 5 continents. Finally, 41 full papers, authored by 119 researchers from 4 countries spanning 2 continents were selected for presentation at the conference and for publication as chapters in this book. I-4AM has grown, starting from a humble beginning in 2019 with 28 papers to the current 41 papers with over 140 people who attended the conference.

I-4AM 22 had 41 papers presentations followed by discussion. It had eight academic keynotes from prominent researchers and practitioners from around the world such as Diane J Mynors from Brunel University London, UK, Paulo Bartolo from Nanyang Technological University (NTU), Singapore, S N Omkar from Indian

Institute of Science, Bangalore, India, Soundar Kumara from Pennsylvania State University, USA, Satyandra K. Gupta from University of Southern California, USA, Seeram Ramakrishna from National University of Singapore, Singapore, Ashutosh Tiwari from The University of Sheffield, UK, and Manoj Kumar Tiwari from NITIE Mumbai.

It had two Industrial keynotes from prominent industry and organisations around India, such as Giridhar M Prabhakar from Siemens Technology and Services Limited, India, and Ms. Nidhi Chhibber from DHI GoI, India. It had three panel discussions: "Industry needs for I-4.0 & AM"; "Manufacturing Needs of the strategic sector"; and "Industry needs for training and education in manufacturing". Over thirty thought leaders from industry, academia and policy sectors participated in the panel discussions.

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About This Book

This book, Industry 4.0 and Advanced Manufacturing—Proceedings of I-4AM 2022, focuses on the following topics:

- Controls, Autonomous Systems, Robotic
- Digital Manufacturing
- Industry 4.0
- Materials Processing and Joining
- Policy and Entrepreneurship
- Supply Chains
- Sustainable Manufacturing

On behalf of the Steering Committee, Advisory Committee, Organising Committee and Co-chairs, we thank all the authors, delegates, institutions and organisations that participated in the conference. We also thank the members of the International Programme Committee for their support in reviewing the papers for I-4AM 22, which is essential for maintaining the quality of the conference, and for their support in helping us put this book together.

We are thankful to the major sponsors (Indian Institute of Science and Springer); other industry partners (Ashok Leyland, Tata Consultancy Services (TCS), Yaskawa, Toyota Kirloskar and Faurecia) and partnering departments (Centre for Product design and Manufacturing, Robert Bosch Centre for Cyber Physical Systems, Department of Aerospace Engineering, Department of Electronic Systems Engineering, Department of Electrical Communications Engineering, Centre for Sustainable Technology, Department of Instrumentation and Applied Physics, Department of Civil Engineering, Department of Materials Engineering, Department of Mechanical Engineering and Department of Management Studies) for their kind endorsement of I-4AM 22. We thank the Indian Institute of Science (IISc), Bangalore, and its Centre for Product Design and Manufacturing, for their support of this event by allowing their employees and students to be involved for the various functions at the conference. We also wish to place on record and acknowledge the enormous support provided by Mr. Venu Allam, Mr. Karthick B., Ms. Nishath Salma, Dr. Shakuntala Acharya, Mr. Kiran Ghadge, Mr. Puneeth K. S., Mr. Ishaan Kaushal, Mr. Apoorv Bhatt, and Mr.

Anubhab Majumdar of IISc in managing the review process, in the preparation of the conference programme and booklet, and for their help in preparing this book and the conference as a whole. We also thank the large and dedicated group of student volunteers of IISc Bangalore for the organisation of the conference. Finally, we thank Springer and its editorial support team, especially its Editorial Director Ms. Swati Meherishi, for their wonderful support.

Bengaluru, India

Amaresh Chakrabarti
Satyam Suwas
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Controls, Autonomous Systems, Robotics

Articulated Robotic Arm for Feeding

Abhived Nair, Devan Rajendran, Joel Chacko Jacob, Nikhil Shobu Varghese, and P. S. Suvin

1 Introduction

Our primary objective was to design a mechanism with adequate degrees of freedom on CAD software. In robotics, a robot's workspace is defined as the set of points that can be reached by its end-effector or, in other words, it is the space in which the robot works, and it can be either a 3D space or a 2D surface. Hence, the primary design requirement of our robot is to ensure that the user's mouth and the plate or bowl from which food is picked up are within the robot's workspace. Another additional requirement is having an end effector to fulfill the given task. The design will also have to account for easy assembly and disassembly and will have to include parts that can be quickly 3D printed or laser cut. Following this, our next objective was to give the robot the sensing capability required to not only identify a face but also to distinguish the user's mouth from other facial features, and defining the mouth location with respect to the robot. This would require employing the user of image processing and machine learning and developing an algorithm to make an approximation of the user's mouth's location from the obtained camera feed. Our next objective was to develop algorithms to both calculate the required motions to reach the robot's destination and subsequently control the electronic peripherals (servo motors) involved to reach those locations. This algorithm would need to be dynamic in nature, i.e., should be able to respond to changes in the user's face location. The final objective of the project was to develop a scaled down prototype with the help of 3D printing and laser cutting, and integrating the previous segments to demonstrate a proof of concept.

A. Nair · D. Rajendran · J. C. Jacob · N. S. Varghese (✉) · P. S. Suvin
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2 Literature Review

Yousuf et al. [1] provided an overview and an architecture for Robot Arm movement and manipulation using ROS and MoveIt and Rviz software that we could possibly use to both control and simulate the robot. Hernandez-Mendez et al. [2] explain the integration of a robotic arm with a motion planner (MoveIt) and a 3D viewer (Rviz), similar to the previous paper but implemented in a different application. Almurib et al. [3] explored the design of an industrial manipulator, different classifications and various other design-oriented aspects of existing manipulators in today's industry. The inspiration for the initial design of our robot was obtained from this paper Farman et al. [4] explored the design of a 3DOF arm, and though our project aims to build a 4DOF arm, various aspects of the same could be implemented for our application as well. Yap et al. [5] discuss a methodology for improved image processing for human facial analysis and try to integrate results from the visible images with the corresponding thermal images. The methodology employed could be used for the sensing phase of our project. Sharif et al. [6] conducted a study comprised of three phases, i.e., face detection, facial features extraction and face recognition. This will be necessary for our code to distinguish the mouth from the rest of the face for our application. Lastly, eye and mouth state analysis is an important step in fatigue detection. Ji et al. [7] proposed an algorithm that analyzes the state of the eye and mouth by extracting contour features.

3 Methodology

The feeding process begins with the detection of the user's face and mouth through the camera through computer vision. Once the user's mouth has been identified, we then compute the location of the mouth with respect to a predetermined reference point. The location coordinates are then sent to our microcontroller, which computes the required positions of the end effector, and subsequently the required movements of the arm using inverse kinematics. These movements are translated into a sequence of servo angle movements. The required feed action is performed, and the bot repeats this process until requested to stop. The figure below represents the flow of operations for the project (Fig. 1).

4 Design of the Arm

In planning the design of the robot, the following considerations were made for the required application. The robot should be capable of exhibiting enough mobility and a variety of different motions. Hence, it was decided that an open loop chain (articulate robot) with the following degrees of freedom would be used:

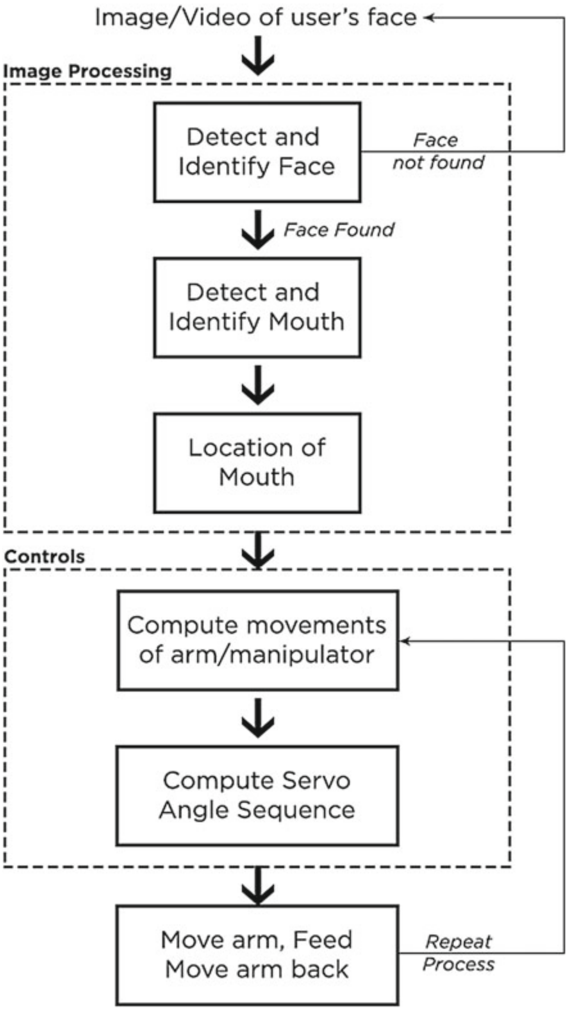

Fig. 1 Methodology flow diagram

- Rotation about the y-axis (revolving base)—1 degree of freedom, 1 revolute joint
- Movement in the xy-coordinate plane—2 degrees of freedom, 2 revolute joints
- End effector mobility—wrist like movement, 1 degree of freedom, 2 revolute joints
- Hence, total degrees of freedom: $2 + 2 + 1 = 5$.

Note: While the wrist-like movement for the end effector was included in the initial design, it was omitted from the development of the scaled down prototype due to manufacturing constraints. The developed prototype hence had four degrees of

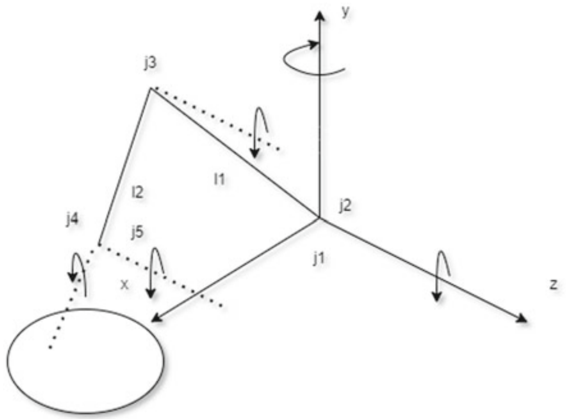

Fig. 2 Open Loop Chain diagram of the robotic arm

freedom. The robot should be capable of reaching the plate, i.e., end effector should be long enough to reach the base or platform i.e., length of link 2 should be greater than or equal to link 1. The robot should be capable of reaching the user's mouth—the length of links should be designed such that the robot is able to extend sufficiently enough to reach the user's mouth. Hence, $28 < l1 + l2 < 36$.

Beyond the above considerations, it was also important to ensure that the weight of the links combined with the above length does not exceed the torque rating of the servos being used (10 kg cm). Since the location of other peripherals such as the sensors, plate containing the food, the microcontroller and onboard electronics cannot be arbitrarily placed by a helper or user, it was decided that a tray-like platform be used to house any other essentials (Fig. 2).

5 Manufacturing and Assembly

The manufacturing process for the full-scale design involved 3D printing the individual links and components. 3D printing or additive manufacturing is a process of making three-dimensional solid objects from a digital file, which was obtained by converting the SolidWorks parts that were modeled into .stl files for 3D printing. The material used for the parts that were 3D printed (end effector in prototype) was PLA plastic (polylactic acid). The parts that were laser cut were laser cut out of a 1.8 mm acrylic sheet.

In the prototype, the links of the arm and the components that make up the base were first modeled in 2D using AutoCAD. Then these were then saved as.dxf files and subsequently laser cut out of an acrylic board (Fig. 3).

Fig. 3 The link after getting laser cut

The end effector was modeled on Solidworks, converted into a .stl file and was 3D printed (Fig. 4).

Once all the individual parts were acquired, Araldite was used to fix the waist link to the base plate, and castor wheels were fastened onto the platform to support the base (Fig. 5).

The remaining links were attached to the servos using fasteners, and a plastic spoon was inserted into the end effector and tightened. Shown below is the developed prototype (Fig. 6).

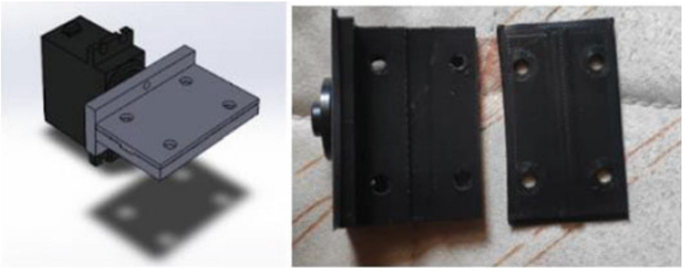

Fig. 4 Solidworks model and 3D printed model of end effector

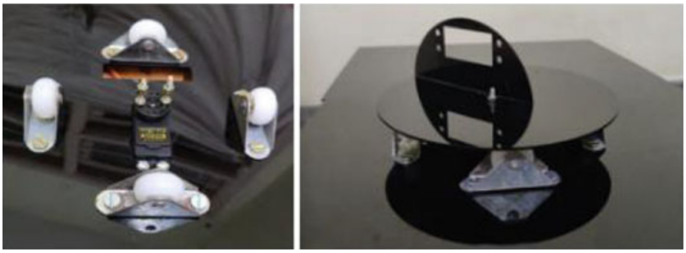

Fig. 5 Manufactured base link

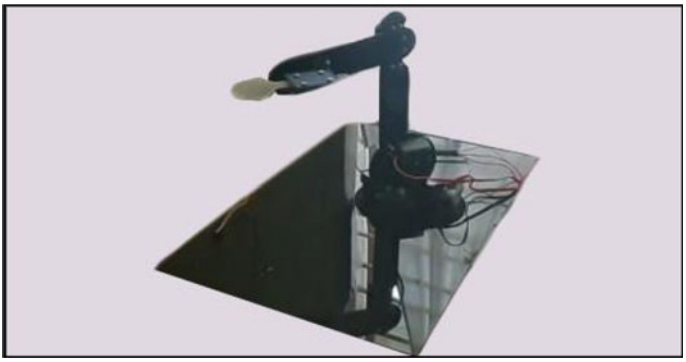

Fig. 6 Final assembly of the model

6 Motion Planning

The motion that our robot has to perform to achieve the given task can be classified into two. Firstly, the motion is associated with filling the spoon. This motion required the end effector to reach the plate, move across the plate, all the while keeping the end effector parallel to plate to ensure no food spills. This motion is repetitive in nature, and hence a single, pre-programmed algorithm to perform the motion would be sufficient. The next motion involves feeding the user. This motion is relatively simple as it requires the robot to reach the user's mouth, based on the location of the mouth determined by the face detection algorithm. This segment of the motion planning algorithm requires the robot to be dynamic and capable of recalculating the angles required to reach the user's mouth each time it needs to feed the user, and hence cannot be pre-programmed.

The motion of our robot is determined by the joint angles of the robot. The joint angles required to reach a specific position are determined using Inverse Kinematics. Matlab offers two solvers for Inverse Kinematics, they are the Inverse Kinematics solver and the generalized Inverse Kinematics solver. The latter is a much more complex solver that allows the designer to input the necessary constraints. A feature is not available in the Inverse Kinematics solver. The three constraints set up for our solver were:

1. Position: This is the target location or point in space we want the robot to reach.
2. Orientation: This constraint allows us to specify that we want the orientation of the end effector to be parallel to the x = 0 line (parallel to the platform and plate).
3. Joint: This constraint allows us to ensure that for any solution, link 1 does not cross the x = 0 line. This is necessary because the solver has a tendency to return solutions where a link is below the x = 0 line, which is impossible in a real-world scenario as that would mean the link is going through the plate itself.

The control of the robot was executed using an Arduino UNO microcontroller. Instructions in the form of servo angles were written on Python using the pyfirmata library, and sent to the Arduino. The actuators involved in executing the movements of the arm were Tower Pro MG995 servo motors.

7 Simulation Results

The graph displayed below is a screenshot of a simulation that was run to test whether the output of the motion planning algorithm yielded usable results. As can be seen from the graph, the motion from (x = 10,y = 5) to (x = 30,y = 5) represents the motion where the spoon held by the robot scoops the food from the plate in front of the user, and the motion from (x = 15,y = 5) to (x = 15,y = 15) represents the robot retracting after scooping the food, while keep the end effector (spoon) parallel to the table to avoid spillage (Fig. 7).

8 Image Processing

A live camera feed was set up and run with the help of the OpenCV module of Python. Each processed frame is passed through the DLib frontal face detector, and a face is detected in the camera frame. 68 Facial landmarks are, thus, identified on the detected face with the help of the DLib shape predictor trained with the 68 facial landmarks data. Mouth and eye coordinates are then extracted from the different their respective landmarks. The calculated coordinates are then converted to cms with the help of a conversion factor, and the depth is calculated with the help of the

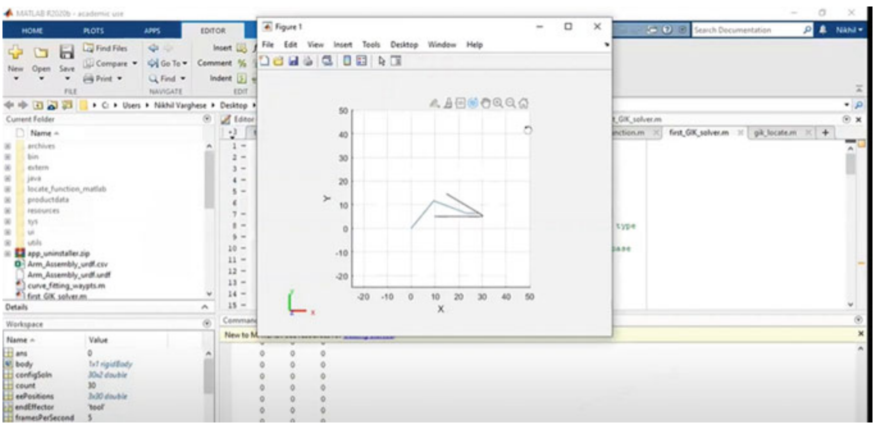

Fig. 7 Simulations result

law of similar triangles. Hence, (X, Y, Z) coordinates of the mouth in 3D space are obtained. The compiled code for the bot, including the motion planning algorithms, can be found in the link below: https://drive.google.com/drive/folders/1lWfI2T2MgLD8nZhFwk-pamSJ6av41GBv5?usp=sharing (Figs. 8, 9 and 10).

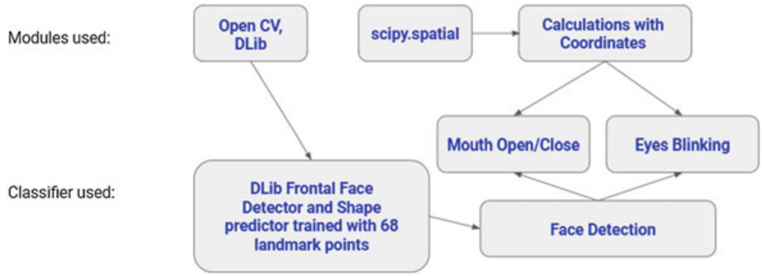

Fig. 8 Modules functionality flowchart

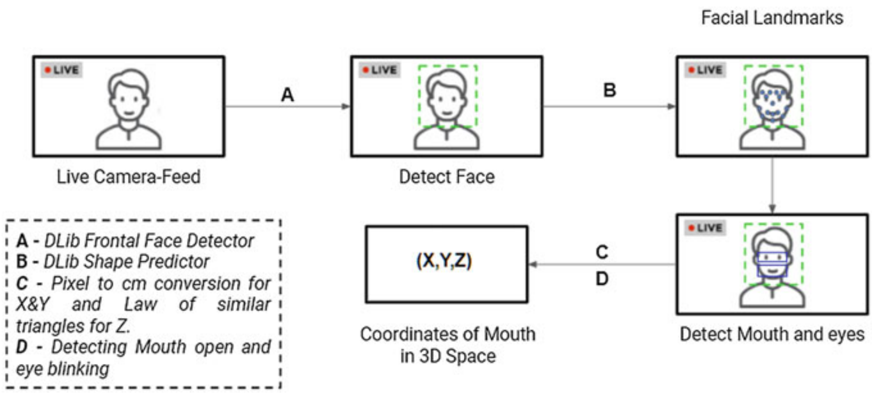

Fig. 9 Image processing workflow

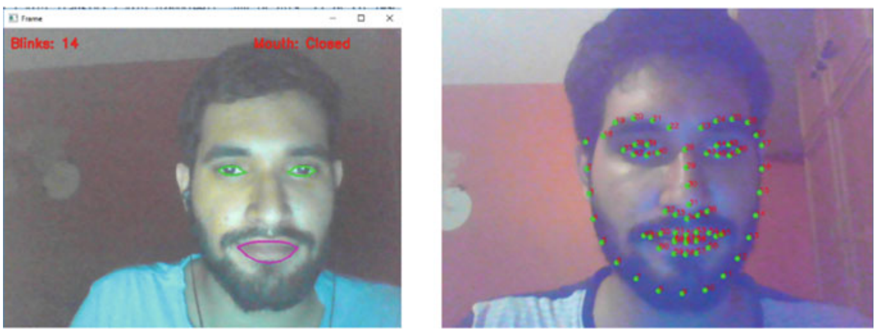

Fig. 10 Eye and mouth detection

Fig. 11 R.A.F.P. GUI application

9 GUI Application

A simple GUI (Graphical User Interface) application was made with the help of the Tkinter module in Python, to facilitate the interaction between the user and the bot. The application in its current state has simple functionalities like choosing the utensil and starting and stopping the bot (Fig. 11).

10 Conclusion

The working of the robotic arm was then tested with a bowl of uncooked rice and keeping a friend as the user. The test turned out to be quite successful with the robot accurately detecting the coordinates of the mouth of the user and executing an accurate yet slightly jerky movement to deliver the food into the user's mouth. In conclusion, by the end of this project, we have developed an algorithm to detect and locate the user's face using Python's dlib library, developed the necessary motion planning algorithms using Matlab's generalized Inverse Kinematics solver, designed a model of the entire product on SolidWorks, and manufactured a scaled down prototype as a proof of concept. Beyond our initial objectives, we have also developed an app with a user friendly interface to control the robot and demonstrated a fully automated feed cycle that requires minimal human intervention.

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Autonomous Navigation for Mobile Robots with Sensor Fusion Technology

Vikram Raja, Dhruv Talwar, Akilesh Manchikanti, and Sunil Jha

1 Introduction

In today's world, the usage of mobile robots has significantly increased in factories and industries for various applications. The main challenge of these mobile robots is that they should autonomously navigate in a random environment, which involves localization and mapping using SLAM (Simultaneous Localization and Mapping). LiDAR (Light Detection and Ranging) is the most common sensor, which is used for gathering the data from the environment for the SLAM.

LiDAR sensors can collect either 2D data or 3D data as point cloud, but 3D LiDAR sensors are significantly more expensive than their 2D counterparts. Also, 3D LiDAR sensors need to be steady and stable during data acquisition, and data processing is more complicated [1]. So, when it comes to affordability and fewer data processing complications, 2D LiDAR sensors are used. Although a 2D LiDAR can do localization and mapping at an affordable price, it cannot detect some of the objects in front of the robot due to its physical properties such as color, reflectance, and size. Nobile et al. explain the limitation of a 2D LiDAR is not able to detect objects, which are either too small or out of the LiDARs field of view, and proposed a method by combining the point cloud data from RGB-D camera to the occupancy

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grid from the 2D LiDAR data to avoid undetected obstacles or obstacles in the blind spot of the 2D LiDAR [2]. This method utilizes point cloud data and requires heavy computation for fusing it with the occupancy grid. Pang et al. compare 3D and 2D LiDARs both horizontally and downward placed, for obstacle detection, concluding high processing time with 3D LiDARs and failed detection of obstacles smaller than the scanning height for the horizontally placed 2D LiDARs, and proposed a novel obstacle detection method by using a single downward oriented 2D LiDAR [3]. This method saw some limitations in detecting dynamic obstacles.

Motivated by improving upon the shortcomings of the 2D LiDAR, in this paper, a supporting vision-based method is used and fused with the primary 2D LiDAR sensor to improve the current mapping and navigation to adapt to the dynamic parameters of the environment. The advantage of this method is that it does not depend on a point cloud data either from a depth camera or a 3D LiDAR, thus making it computationally light, is able to detect dynamic obstacles and can utilize any monocular vision camera for object detection purposes.

2 Approach and Implementation

This paper explores the idea of using an image sensor, which eliminates the limitations caused by the 2D LiDAR. The vision sensor is used for detecting objects, which are missed by the 2D LiDAR, and a pseudo laser scan is published based on the object that is detected. These published pseudo laser data are then fused with the original 2D LiDAR scan data array to completely detect any obstacle in front of the robot. Figure 1 outlines the overall system process structure where the 2D LiDAR and vision sensor data are fused to get the desired results [4].

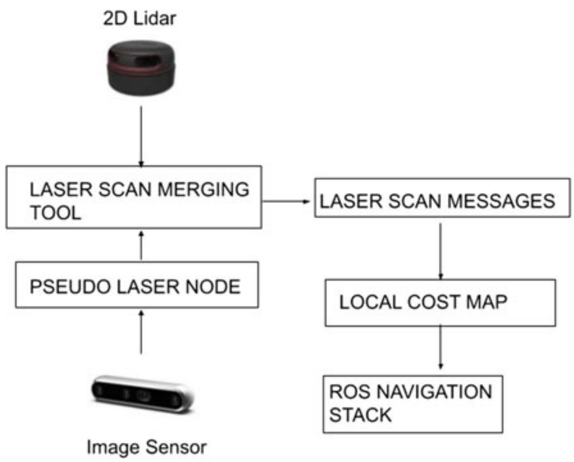


Fig. 1 Fusion of laser scan data for passing information to the navigation stack

While the robot is in motion if an object is in front of the robot usually LiDAR will detect them and then it updates the local cost map in the ROS navigation stack for avoiding the obstacle but if the object is at a height lower than the LiDAR plane or due to the objects properties the LiDAR is unable to detect it, then the image sensor will be used. The image sensor uses YOLOv3 a deep learning-based object detection that detects the object using neural networks. After detection, it sends the message to the pseudo laser node that an object is detected. The pseudo laser node after receiving the message it sends false laser scan values, which are updated in the local cost-map for avoiding the obstacle in front of the robot.

2.1 Vision System Implementation

The vision system uses a hybrid neural network known as YOLOv3 [5]. YOLOv3 is a deep learning object detection algorithm that recognizes certain objects in images. The objects that need to be detected are first trained in the neural network by tuning the weights and then it is deployed. YOLO is much faster than other networks. As shown in Fig. 2, YOLO-V3 uses a Darknet-53 model network, which has 53 convolutional neural network layers and Res-Net-like skip connections [6].

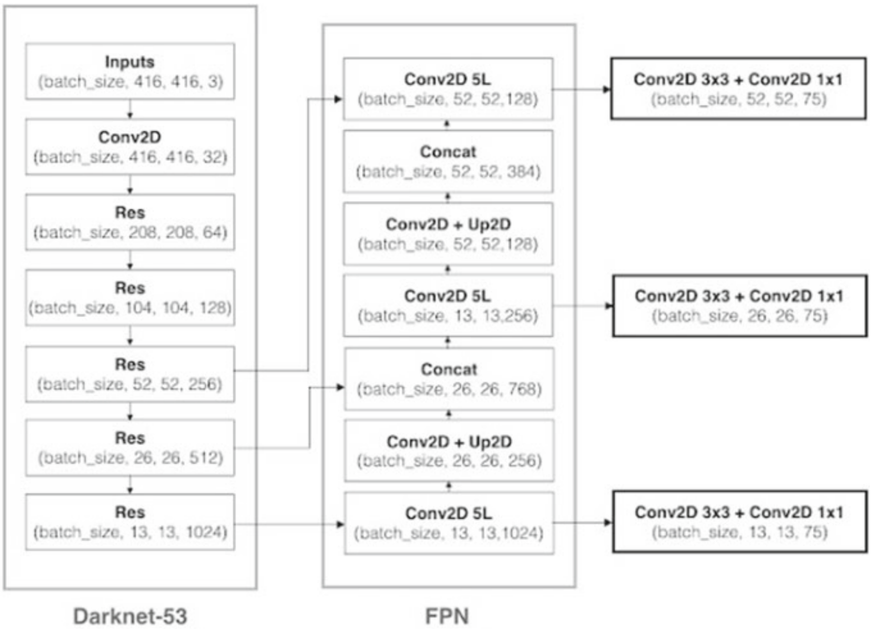


Fig. 2 YOLOv3 architecture (*Source* kaggle.com)

YOLOv3 also includes a feature pyramid network that detects objects of different sizes. The output of the feature pyramid network is known as a grid. In each of these grids, three anchor boxes with the same centroid of different lengths and breadth are placed on it. The applied anchor boxes predict the predefined class name and the location of the object within the image. Thus, the bounding boxes are applied to the image. Networks like R-CNN (Region-based Convolutional Neural Networks) and Fast R-CNN (R-CNN improved) are almost like YOLOv3. The main difference between R-CNN and YOLOv3 is that YOLO is trained to do classification and bounding box prediction simultaneously [7]. From Fig. 3, it can be observed that the YOLOV3 has the second-best mAP (Mean Average Precision) score and has less interference time. In this simulation, pertained weights were used, which contained 80 predefined classes. As shown in Fig. 4, the object, fire hydrant is detected in the gazebo environment.

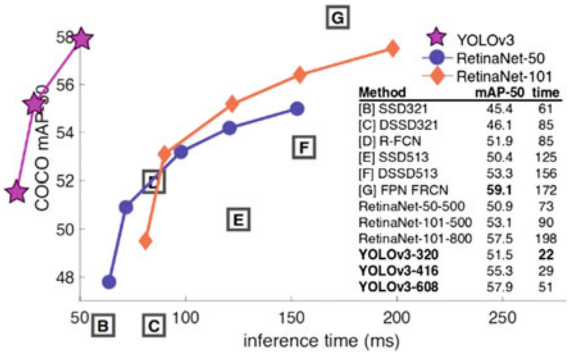


Fig. 3 Comparison of YOLOv3 with other object detection methods (*Source* towardsdata-science.com)

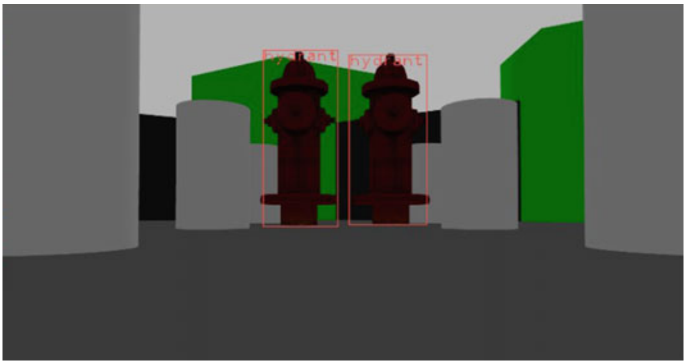


Fig. 4 Detection of fire hydrant class object in Gazebo environment

2.2 LiDAR Sensor Integration

For this robot simulation, Hokuyo laser sensor plugin is used here to get laser scan values from the gazebo environment. These laser scan values are published under the LiDAR scan sensor messages within ROS environment. Hokuyo Node (UTM-04G) can scan up to 270° with a range up to 4 m. This sensor is used for localization and mapping. Figure 5 shows that Hokuyo LiDAR sensor is mounted on top of the robot indicated in red color.

2.3 Robot Motion Using Four-Wheel Mecanum Drive

Mecanum wheel is also known as the Swedish wheel or Ilon wheel uses complex designed wheels that enable the robot as shown in Fig. 6 to move in any direction in the absence of changing the orientation of the robot. A mobile robot with ordinary wheels must turn or steer to change the direction of the motion but a Mecanum robot can move in any direction without turning.

The Mecanum wheel has rollers of rubber material that are diagonally attached to the circumference of the wheel frames as shown in Fig. 7. The roller's axis of rotation is at an angle of 45° to the plane of the wheel. The main advantage of the Mecanum wheel is that it provides high maneuverability and mobility in crowded environments. In this project, gazebo simulation is used so that four-wheel skid drive and planar move plugins are used here to produce holonomic drive.

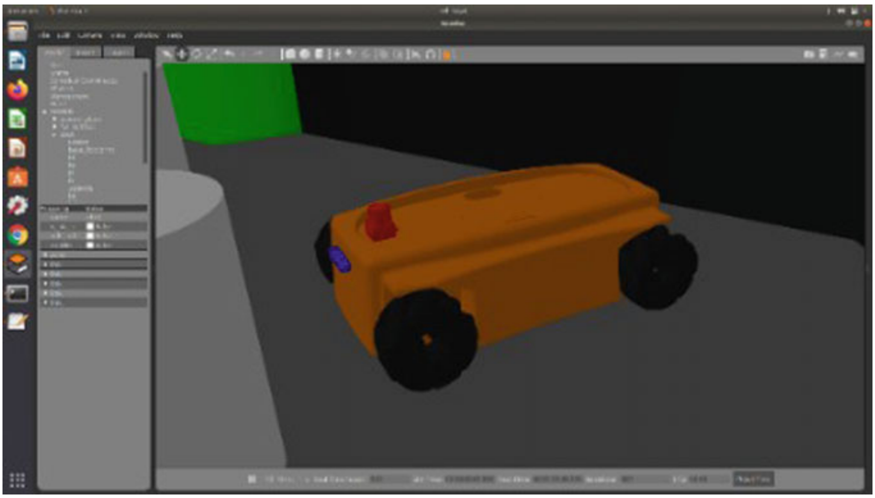


Fig. 5 LiDAR Sensor mounted on robot

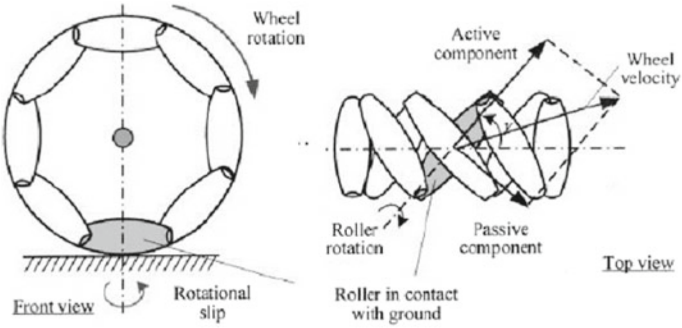
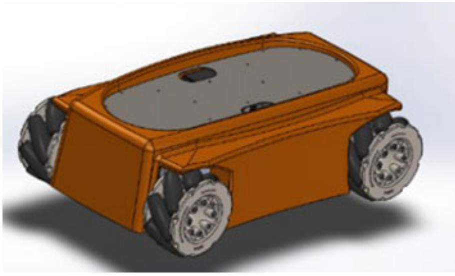


Fig. 6 Wheel velocity direction [8]

Fig. 7 CAD model of robot with the Mecanum wheels



2.4 Mapping Environment Using GMapping

The mapping algorithm utilizes a Rao-Blackwellized particle filter for the pose estimation of the robot on the map. In this approach, the algorithm takes laser range data and odometry values for more accurate position estimation. For an indoor environment with a lot of features, the particle filter-based approach can estimate the pose of the robot with good performance as shown in this study [9]. GMapping is available as a package in ROS, which provides laser-based SLAM. Using GMapping, a 2D map can be created, which can be used for goal point navigation. In Fig. 8, it can be observed that the mapping of the turtle house world in gazebo is done through ROS GMapping package.

2.5 ROS Navigation Stack

The Navigation Stack acquires odometry values and laser range values from encoders and laser sensors, respectively. After computation, it produces velocity values under the topic command velocity to the move-base node as shown in Fig. 9. Navigation stack can be applied for both differential and omnidirectional robots. It requires a

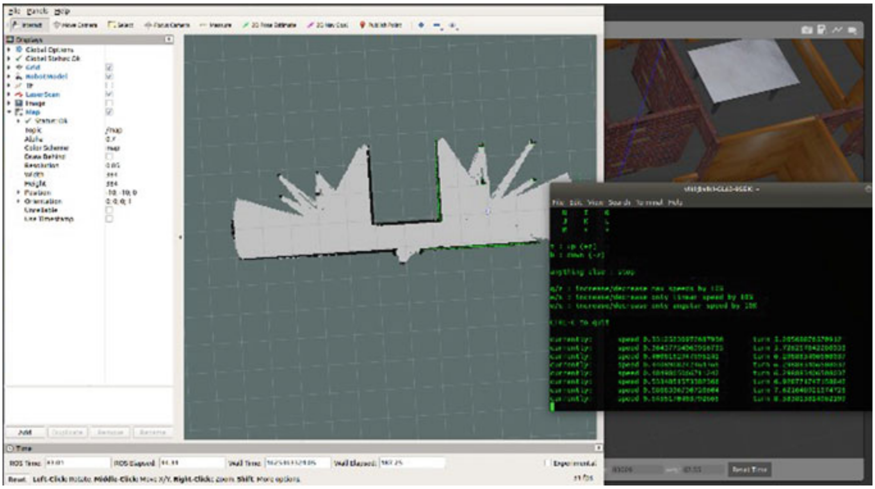


Fig. 8 Mapping of turtlebot house world

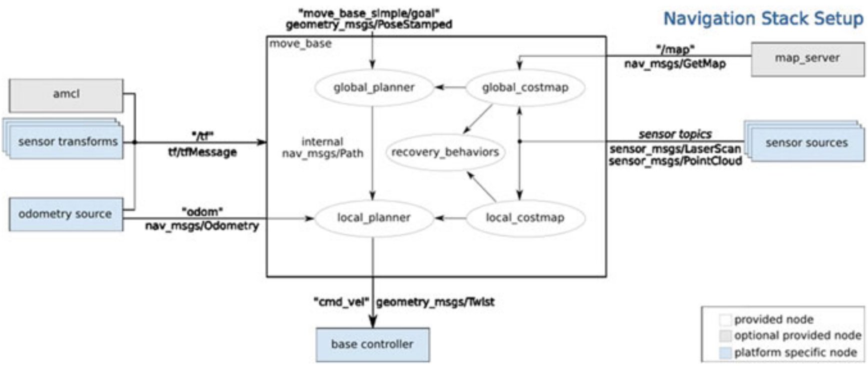


Fig. 9 Navigation stack system process (*Source* edge.rit.edu)

laser sensor mounted on the mobile base. This laser sensor is used for localization and mapping. The Navigation Stack cannot be applied on arbitrary shaped robots as it was developed for a square or circular shaped robot. It uses global cost map and global planner for planning a route to a goal position using the preloaded map, and it uses local cost map and local planner for avoiding the dynamic obstacles in the environment. As the robot used in the simulation is a holonomic one, thus the AMCL parameters need to be changed to holonomic configurations, and Y-axis velocity should be added in local planner parameters [10].

2.6 Vision-Based Pseudo Laser Node

ROS navigation stack receives the laser scan data through sensor messages. These messages are produced by the LiDAR device drivers. These messages can also be produced manually by simple python programs. The objects that are not able to be detected by LiDAR will be detected by the image sensor so whenever an object is detected by vision system, the pseudo laser node receives the message from the object detection node. After receiving the message, the pseudo node produces laser values at the distance where the object is located pretending that an object is in front of the robot as shown in Fig. 10.

2.7 Sensor Fusion: Laser Scan Merger

To merge the pseudo laser scan and the actual laser scan, an Ira laser scan merger is used. Ira laser merger is a ROS package that allows merging multiple 2D laser scans into a single one; this is very useful when a robot is equipped with multiple single plane laser scanners. The output scan will appear as generated from a single scanner as shown in Fig. 11.

2.8 Implementation of Fused Sensor Outputs

In this simulation, the object, a fire hydrant, is placed in front of the robot. As these objects are smaller in size, the LiDAR is unable to detect them but the vision system detects these objects as shown in Fig. 12, and then it sends a message to the pseudo laser node, which eventually produces a laser scan at the distance where the object is located [11]. The newly produced laser scan is updated in the local cost map, which

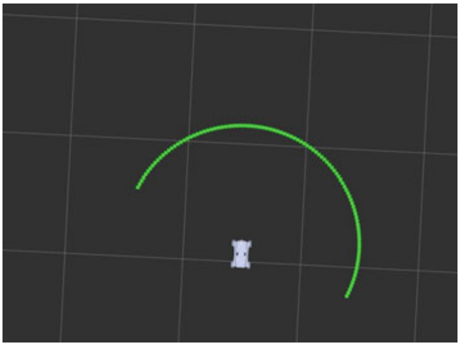


Fig. 10 False laser scan visualization

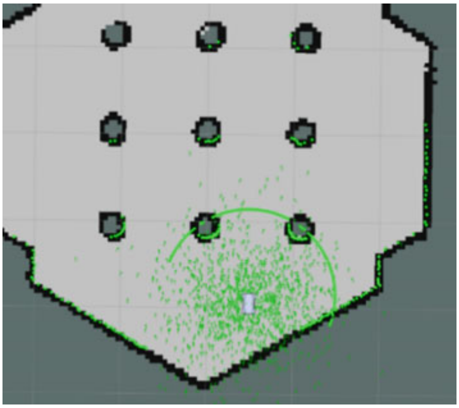


Fig. 11 Combined laser scan values

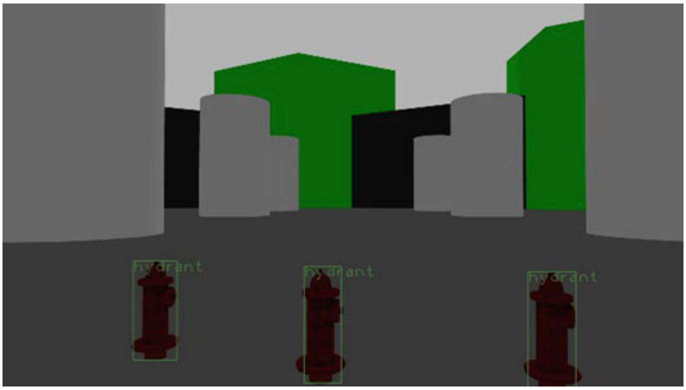


Fig. 12 Objects detected by vision sensor

makes the navigation think that an object is detected in front of the robot and makes the global planner plan a new path where the fire hydrant object is avoided.

In Fig. 13, it is observed that the goal point is straight ahead of the robot, but the robot refuses to take the straight path because the fire hydrant object is detected by the vision system, so it takes another path.

3 Results and Discussion

In the final simulation, objects that were small were placed in front of the robot. The 2D LiDAR due to the height of the object is unable to detect it, and the image sensor successfully detected them. Due to this detection, the pseudo laser node updated the

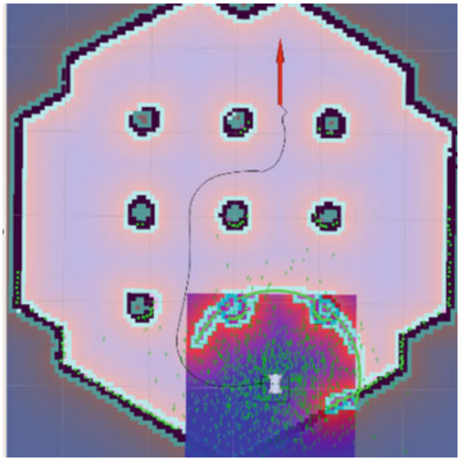


Fig. 13 Robot taking alternate path

cost map that an object is ahead of the robot, which made the robot take an alternate route to reach the goal position as shown in Fig. 13. However, during the simulation, it was found that the usage of a single camera cannot solve the whole problem because if the object is behind no sensors can detect that so usage of a 360° camera or other sensors such as TOF sensors will be able to solve this issue.

4 Conclusion

In this simulation, the limitations caused by the 2D LiDAR sensor are eliminated by using an image sensor and deep learning algorithm, where if the LiDAR fails to detect the object, the image sensor helps the LiDAR to detect the object and successfully able to update the cost map and provide actual obstacles navigation path. This method can be deployed for industrial mobile robots, which aim at material movement especially those mobile robots that are deployed in a dynamic indoor environment. This method can also be used for industries that are looking to buy 2D LiDARs as an affordable option, which eliminates the need for 3D LiDARs.

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Design of Robotic Model Using White Line Sensor-Based Autonomous Carrier Robot in Industrial Applications: Task and Performances for Validation

S. Narendhiran and M. Velan

1 Introduction

There are many gaps and needs to be fulfilled on the automation of various components and their functions in sectors like healthcare and industrial operations. Primarily, in production environments, the need for transportation carrying small parts in large quantities within the premises is tremendous [1, 2]. However, because of the task's simplicity, lower valuation and repetitive nature, humans tend to perform tasks with reduced concentration levels, resulting in increased human-related error during performance. Over the survey, almost 40% of jobs performed every workweek were repetitive tasks for at least a yearly-quarter in the production line. In addition, nearly 90% of accidents that occur in the workplace are due to human-related errors [1, 3]. According to the survey, introducing automation for daily work will improve productivity and reduce squandered time appreciably by eliminating human-related errors. Furthermore, the repetitive work can be automated by 30% before the early 2020s to increase efficiency [2–4].

Artificial intelligence-based applications have proven more vast performance improvements by substituting human interactive tasks [1, 6–8] in smart manufacturing, clinical practices, assistive nursing schemes in large hospitals and healthcare centres [3, 9, 10]. There have been several applications in the recent past on the gradual implementation of line following robots in industries and commercial sectors [11, 12] with artificial intelligence array orientations, resulting in saving time and minimizing the human-related error, and enhancing resources utilizable capacity. The line following robot was visualized and applied in many industrial sectors, human-assisted factories and clinical organizations in achieving the targets assigned for job

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displacement and job replacement [13–15]. On the eve of emerging robotic intelligence and applications, the assistive mechanical schemes were designed to support manual employment and machined deployment over many industries and healthcare monitoring systems [16–18].

The workflow system is being implemented for line follower robots overcoming the issues and challenges in the case of a General Hospital [20], involving all emergency operations necessitating a result-oriented performance [18, 19]. Automation is essential in other sectors, namely health sectors, where healthcare-associated infections (HAIs) have a tremendous impact on the quality of health workers. Furthermore, HAIs are a type of infection when people are affected by a new illness while receiving treatment for another condition. According to the reports from the Centers for Disease Control and Prevention (CDC) taken in 2015, 4% of hospitalized patients are infected with one or more HAIs [3, 5] and 687,000 HAIs were estimated in U.S. acute care hospitals during 2015 [4, 19]. Although significant progress has been made in preventing some HAI types, CDC said that much more work needs to be done. Continually, it is evident to frequently sanitize the contaminated environmental surfaces to avoid cross-transmission of pathogens. Herein, the introduction of the autonomous robot with line following mechanism is to sanitize the contaminated surface for the prevention and control of HAIs and also with expected frequent movement of people (obstacles) in the hospital area, using a similar obstacle detection algorithm as discussed in the production line for implementation [25].

2 Methodology

2.1 Problem Definition

The proposed robotic prototype's theme is to implement in the healthcare sector or production line environments to substitute repetitive and recurring jobs. The mechanical prototype follows a black line to perform tasks, and it is also programmed to manoeuvre the possible interference of any unpredictable non-static obstacles in its path by finding other possible shortest routes to reach the destination. Some of the tasks performed are picking and placing the materials at varied elevation levels.

2.2 Constructive Equipment of Industrial Robotic Model

ATmega2560 development board. It is a microcontroller of the AVR family. Similarly, microcontrollers are a brain in robots like a brain in human beings. It takes the input from sensors, processes it and controls the actuators (D.C. and servo motor).

L298N motor driver. It controls the motors' speed and direction. The function of this I.C. is to provide the required amount of current to the D.C. motors, which the development board cannot provide as the current supplied by the board is too low.

White line sensor. This sensor detects black/white surfaces by procuring variation in sensor data. It consists of three pairs of transmitters and receivers.

Sharp sensor (proximity). This sensor detects barriers placed close to the robot. Therefore, there is a variation in sensor data in proximity.

Servo motor. It is a rotary actuator for precise control of angular position and velocity. Notably, it provides sufficient torque to maintain its defined position.

Geared DC motor with encoder. The connected encoder measures the shaft's rotational speed and direction and tracks how far the bot has moved linearly.

2.3 Mechanism and Configured Sensor

The robotic prototype involves a line following algorithm utilizing a white line sensor and has several advantages compared to lidar, radar, or camera over 3D visualizing the environment. Also, white line sensors reduce overall robot cost and still benefit from precise travelling using minimum memory requirements, which is easy to process, resulting in a reduced validation period for the robotic model. Similar advantages are found with a sharp sensor over radar: limited sensor data is processed, leading to low runtime, so that a significant amount of sensor data are processed. However, sharp sensors are sometimes unreliable under harsh conditions like natural calamity or diminished lighting conditions, which are inapplicable to closed production facilities or secure healthcare centres equipped with proper lighting conditions. Servo motors are better than stepper motors because they provide high torque at high speed, and it is capable of maintaining at their defined angle with maximum torque even during no operation of servo motor.

2.4 Configuration and Working Scheme

The practically designed field applicable model is an autonomous self-decision-making robot operating with the shortest path planning algorithm. The model was modelled as a low-cost robot design, with two motors and a caster wheel for linear movement (Fig. 1). All the sensors and the motor driver are connected to a microcontroller. The board receives data from the sensors (Fig. 2) and processes it to provide

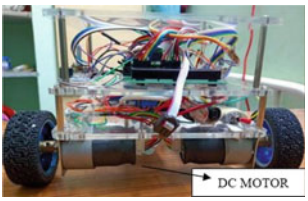

Fig. 1 Rear view

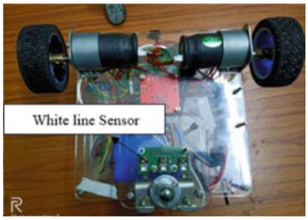

Fig. 2 Bottom view

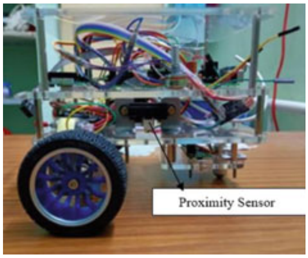

Fig. 3 Side view

commands to the components. The motors are not connected to the development board because of their inability to provide sufficient current to the D.C. motor, so motors are linked via motor driver to control the motors' speed and direction. The sharp/proximity sensor (Fig. 3) is placed in the robot's rear and front end to detect obstacles during any of its operations.

2.5 *Configuration of Accessory and Applications*

The model is then connected to an accessory depending on the robot's purpose. First, a robotic arm is introduced in the system for picking and placing the materials (M, as referred to in functional layout) in production lines or healthcare centres. Secondarily, a sprinkler is attached as an accessory for sanitization in healthcare facilities that sprinkles sanitiser in the robot's surroundings while transversing. Again, the robotic arm consists of two servo motors. One servo motor is employed for the gripper connected to one of the gears (Fig. 4) and controls the rotation of gears. The second servo motor (Fig. 5) is for arm movement, where the servo motor controls the angle of the arm horizontally. The component is mounted in front of the robot (Fig. 6).

Challenges on mounting locations of the arm. Placing the arm at the front necessitates a low arm size requirement, reducing construction costs. In addition to this, the robotic arm is placed in front for better stability as it acts as a counterweight to the two heavy D.C. motors at the back-bottom to avoid toppling.

Fig. 4 Gripper model

Fig. 5 Robotics arm

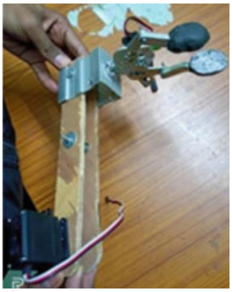

Fig. 6 Robot in field

3 Industrial Prototype Maps

The map shown here is a prototype for this problem statement, and this prototype map (Fig. 7) is designed to mimic industrial and healthcare environments to pick and place the objects at multiple junctions (node), necessitating picking and putting at a varied elevation.

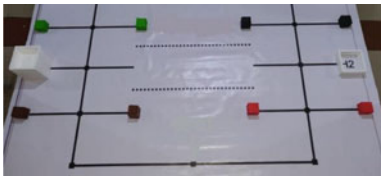

Fig. 7 Industrial prototype map

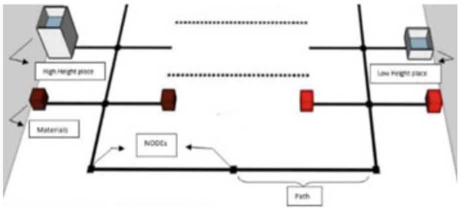

Fig. 8 Prototype map (animated model)

3.1 *Typical Functional Layout: Prototype Map and Target*

Materials (M): Portable objects (cubic-shaped boxes), as referred to in Fig. 8.

Place. A delivery location. There are two types of places: low height place (LHP) and high height place (HHP), consisting of different elevations (Fig. 8).

Path. Locomotive paths (two-way). One receiver pair in a white line sensor detects a black surface.

Node. Junctions in the map (intersections of paths). Two or three receivers in a white line sensor detect a white line sensor.

3.2 *Retrofitting Problems and Rectification*

During the simulation, in reality, there were several challenges faced during construction, and during simulation time the challenges faced are:

Challenge 1. Due to the increased vibration in the robot during fast movement, it is observed that the material (M) might slip from the gripper in a real-world simulation.

Solution 1. By increasing the contact surface area of the gripper (Figs. 5 and 6).

Challenge 2. Our robot is 15 cm in height and picks up the material (M) from 3 cm. The challenge is to pick an L-shaped arm (1 servo) or two movable links (3 servos) for the component.

Solution 2. An L-shaped arm was cost-effective, still meeting the needs (Fig. 5).

Challenge 3. Initially, an LCD helps us calibrate the sensor's cutoff value by displaying sensor reading; the major prior requirement was to decrease the runtime of the sensor data extraction loop code so that the number of extracted sensor data increases significantly, leading to a reduced error rate. However, LCD consumes more time to display the sensor data comparatively. Thus, a reduced number of sensor data fed to the algorithm led to improper line following and improper detection of the path at the junction/node of the map.

Solution 3. The LCD was excluded to remove the lag in the code's runtime. Serial communication was established using Tera-term to log data via the serial port, which provided minor lag issues resulting in the extraction of the maximum sensor data.

Challenge 4. Sharp line sensor-related challenges: When the sensor detects a black surface, the extracted sensor data is dependent on the battery charge level, which leads to the sensor's cutoff calibrating issues.

Solution 4. Three ranges of sensor's cutoff calibrated values were fed based on the battery level of the model after various simulations by trial-and-error methods. Similar challenges have been reported for interactive robotic operative systems [5–8].

4 Implementation in Real-Time Monitoring

4.1 General Hospital U.T. of Puducherry, South India

The specific application and implementation schemes are incorporated regarding a live application in a General Hospital located in U.T. of Puducherry, South India. The particular workflow plate observation connects various operational floors of the hospital, requiring immediate medicine and accessories and task performance of diagnosis in a line orientation array. The simulated workflow using the line following robot is demonstrated in Plate 1. The study reported [8, 9] on the workflow performance of various human–computer interface intelligence converged to similar results of the time dependency and its orientation to newer horizons of real-time monitoring.

The discussion in the works [10, 11] demonstrated clinical layouts and the possible requirements of robotic-assistive diagnostic support in establishing the implementation of automation through practical automated surveillance and monitoring system. Finally, the model was implemented with the observation and orientational assessment of the above-reported study and its retrofitting effects. The application of the work with workflow system is being retrofitted for line follower robot replicating the issues and challenges with that of the real-world monitoring in the case of a General Hospital, involving all emergency operations necessitating for result-oriented performance. The investigation [17–21] revealed a similar trend of work and its performance task through live and responses of robotic interactions under line array.

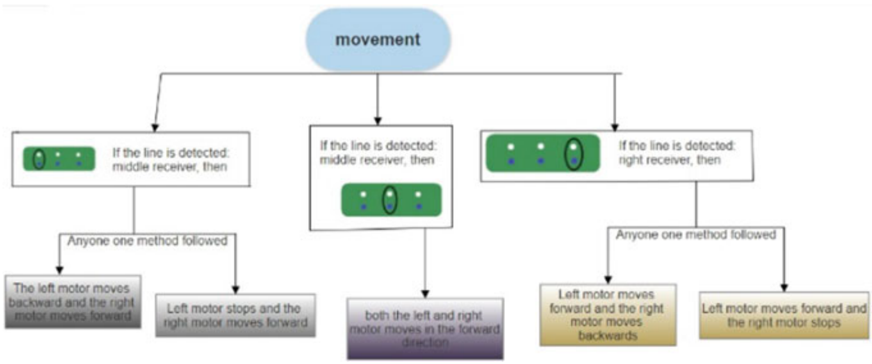

Plate 1 Courtesy from General Hospital functionary workflow-assistive system

4.2 *Government Hospital Workflow Diagram*

The hospital workflow diagram is shown in Plate 1; the application of the Line following robot is indicated for a typical floor of the hospital requiring place and place mechanism-oriented tasks and performing the job to the necessary degree of acceptance. The task performance was demonstrated and assessed in similar trends of work investigated [23, 24].

The findings and performance of the chosen study are inspired by the authors of various investigations such as [20–22] in demonstrating the real-time application and monitoring of line following robot fulfilling time-dependent operations with the specific task performed at different floors and diagnosis.

4.3 *Programming*

The motion of the robot mainly involves basic sensors like a minimum of two motors with an encoder, a microcontroller and a 12 V battery. Every microcontroller has a unique compiler, and C language is used. In this project, we used "ATmega2560," which comprises four parts as separate ports which serve as either an input or output for the motor driver. Initially, the program is stored in the microcontroller's ROM, and the abstracted data from the white line sensor is converted from analogue to digital and will be passed on to the microcontroller in port A. After processing, the algorithm will send individual instructions to each motor via motor driver. The algorithm flowchart is explained in Figs. 9, 10 and 11, where movement is either forward or backward, and the corresponding commands are depicted. The algorithm

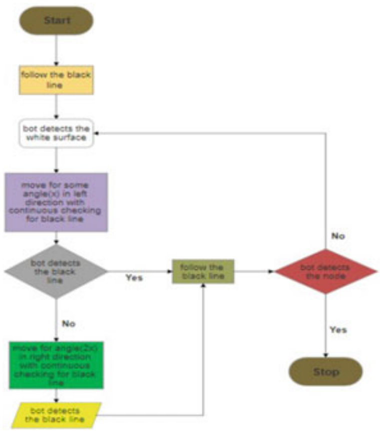

Fig. 9 Flowchart for movement on the black line

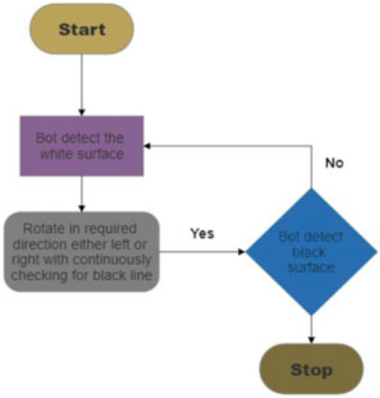

Fig. 10 Algorithm flowchart for the forward motion in the node-line-node

flowchart for the forward motion node-line-node is also stated; the line following code fits for a curved path.

The forward motion is coded for node-line-node in the map, as illustrated. Every time the robot is instructed to pick/place, it finds the shortest possible way. The procedures the robot is capable of performing are forward motion, rotating at any node (as per the robot's decision, ranging from 0 to 360°), picking and placing the object.

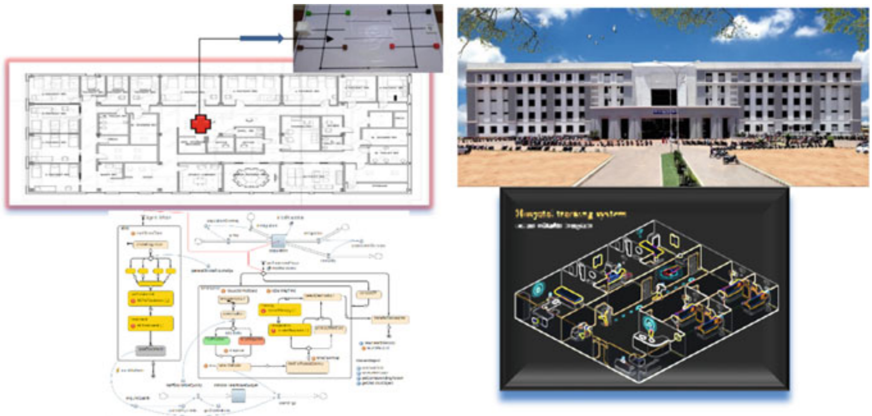

Fig. 11 Flowchart for rotating at a junction (node)

4.4 Typical Forward Movement Algorithm

A piece of code, where the forward motion is designed to transverse from a node-line-node, herein will follow any curved line, as represented in a flowchart (Fig. 9). A typical algorithm presented a “cutoff” value of 50, manually calibrated, and a sensor-dependent value.

```
void forward(int node)
{
// The loop checks sensor’s data with respect to cutoff, which is 50.
while(node>=1)        // “node” means number of nodes that the robot will pass by.
   {
   left_wls_reading = ADC_Conversion(3); // white line sensor data
   middle_wls_reading =  ADC_Conversion(2); // Sensor’s data varies from 0-255.
   right_wls_reading =  ADC_Conversion(1);
   front_ir_sensor_reading = ADC_Conversion(5);

    if(left_wls_reading>cut_off&&middle_wls_reading<cut_off&&right_wls_reading
<cut_off)
   {        left();    }
   else
if(left_wls_reading<cut_off&&middle_wls_reading<cut_off&&right_wls_reading>c
ut_off)
   {        right(); }
   else
if((left_wls_reading>cut_off&&middle_wls_reading>cut_off&&right_wls_reading>c
ut_off)||(left_wls_reading>cut_off&&middle_wls_reading
>cut_off&&right_wls_reading<cut_off)||(left_wls_reading<cut_off&&middle_wls_re
ading>cut_off&&right_wls_reading>cut_off))
   {
      forward(50); // move forward by 50 mm for both motors using encoders.
      stop();
      node--;
   }else
   { //left motor velocity: (250/maximum input value) * maximum motor speed
      //right motor velocity:(255/255)* max. motor speed
      velocity(250,255);
      forward();
   }}}
```

5 Conclusions

The following are the conclusions derived from the present study:

1. The robotic prototype, mechanized with white line sensor-based automotive carrier, was framed and applied for performing the chosen task in Industry 4.0 application.
2. The map's robotic arm tracing functional layout reach the target destiny through simulations fitted for its ultimate target.
3. An inbuilt algorithm with simulation realized the obstacles and found the shortest way to reach the destiny.
4. Retrofitting and validation were done for the simulation to solve tasks and challenges in industrial applications for the chosen application in production line and mobilization.
5. The specific application and implementation schemes are incorporated regarding a live working space in a General Hospital located in U.T. of Puducherry, India and were demonstrated.

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Volume Decomposition of Faceted Models to Minimize Post-processing Issues for Multi-robots Collaborative Material Extrusion Systems

Madhanagopal Manoharan, Chitikena Hareesh, and Senthilkumaran Kumaraguru

1 Introduction

Three-dimensional printing (3DP) is the process in which the parts are built layer by layer from the digital CAD model data. In the case of deposition or extrusion-based 3DP processes, only relatively simple geometry parts can be fabricated with the help of a three-axis CNC machine. It is evident that printing a geometric part with overhang features using uni-directional deposition (UDD) with three-axis CNC requires support structures. But the deposition of high-strength and high-temperature polymers, metals, and ceramics material on support structures is often troublesome from the viewpoint of building and removing them. By considering certain objectives such as high surface quality and lower build time for the parts printed with 3DP, multi-directional deposition (MDD) provides a better solution. This MDD needs unique volume decomposition algorithms to decompose the overhang features and identify the build direction to print those features. The industrial six-axis serial manipulators provide a better solution for MDD and thereby overcome the limited motion capabilities associated with three-axis CNC machines. These robot-based 3DP or AM systems have gained a lot of interest owing to their flexibility to create complex objects without or minimum usage of support structures. Robots are flexible machines that can perform complex trajectories for printing non-planar geometries using the 3D printing technique. Out of seven major additive manufacturing (AM) processes [1], serial manipulators are widely used in polymer-based material extrusion [2] or metal-based direct energy deposition (DED) processes [3]. The six-axis serial manipulator-based industrial robot arm can carry out tasks collaboratively with another serial manipulator. There should not be any collision between the robot

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arms in the generated trajectory paths. Proper collision analysis is necessary for the generated trajectories of these collaborative robot systems [4] before deposition.

Several researchers have made attempts to find the direction of deposition for a multi-directional part using multi-axis systems. Singh et al. used the spherical mapping technique to detect the build direction and silhouette edge for volume decomposition [5]. This silhouette edge technique is recursively used to decompose the part into sub-volumes. An alternate solution for the same volume decomposition by Sundaram et al. is using the surface interrogation technique [6]. In this work, the boundary representation (B-Rep) model is used instead of a faceted representation. This poses greater challenges for free-form surfaces because of the computational complexity. A similar MDD problem for the faceted models was solved by Zhang et al. using surface tension and transition wall techniques [7]. Gaussian maps are used to find the build direction of the decomposed sub-volumes. Even though this method can successfully print features along multiple directions, nozzle collision is a major issue associated with this approach. A similar method developed by Ruan et al. used a geometric recognizing tool to determine the build direction [8]. The centroidal axis gives the topological information of the part and this information is used to determine the direction of build for each layer. Ren et al. combined the modular boundary models and centroidal axis extraction methods to decompose the parts, which eliminate the limitations of the centroidal method [9]. If the centroidal positions are the same for the adjacent slicing layers, then the decomposition method will switch to modular boundary models to eliminate the failure. Ding et al. developed a volume decomposition-regrouping [10] algorithm, which uses a tessellated CAD model for finding the build direction.

From the literature survey, it is found that there is a need to develop a volume decomposition algorithm to decompose the tessellated models in a faster manner. Hence, this work aims to decompose the part volume into MDSV using a concave–convex loop relationship, and those sub-volumes are cumulatively decomposed using the bounding box methodology. This strategy provides quicker results for volume decomposition and eliminates the regrouping of the sub-volumes for a particular build direction.

2 Example Test Parts

The use of supports in 3DP has both advantages such as reduced distortion, complex overhang fabrication, and disadvantages such as surface roughness, material wastage, and larger print deposition time. Figure 1a–d shows the need of supports for the overhang features considered in this study. All the test parts used in this work need support structures for uni-directional part printing using three-axis CNC systems.

The supports in the printed test parts are removed after part fabrication and Fig. 2a–d shows the test parts without supports. The surface roughness in the marked overhang feature surface is analyzed to prove the importance of MAD for improving the build quality in the 3DP parts.

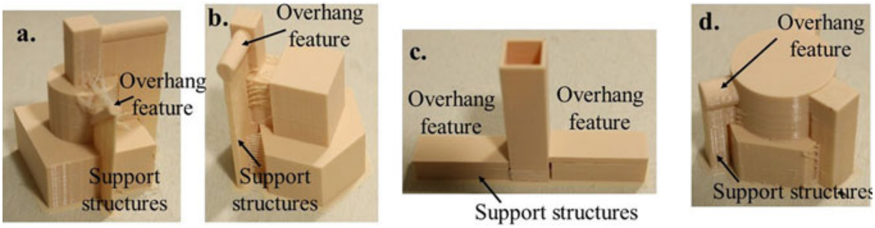


Fig. 1 Test parts with supports **a** Part 1, **b** Part 2, **c** Part 3, **d** Part 4

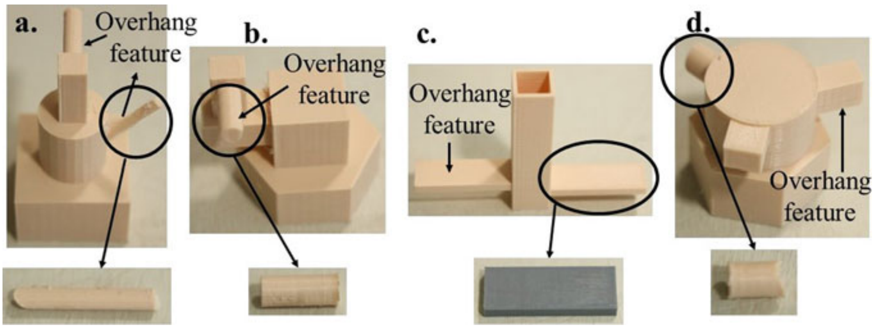


Fig. 2 Test parts after support removal **a** Part 1, **b** Part 2, **c** Part 3, **d** Part 4

For the successful building of the near net shape, a robust decomposition algorithm needs to be developed which overcomes the limitations of the present approaches that focus only on the subset of part geometries. In this work, we implemented a concave/convex-based approach for faceted models by identifying the overhang sub-volumes.

3 Methodology

A robust and speedy algorithm needs to be developed for implementing MDD effectively by decomposing the 3D part and finding the direction of the deposition. The overall methodology of the developed algorithm is shown in Fig. 3, which uses the concave–convex loops and bounding box technique for volume decomposition.

Standard Tessellation Language (STL) file of ASCII format is the input to the volume decomposition algorithm developed in MATLAB. The algorithm initially categorizes the feature edges into concave and convex edges. These edges are the input for the generation of the bounding box for decomposing the overhang features.

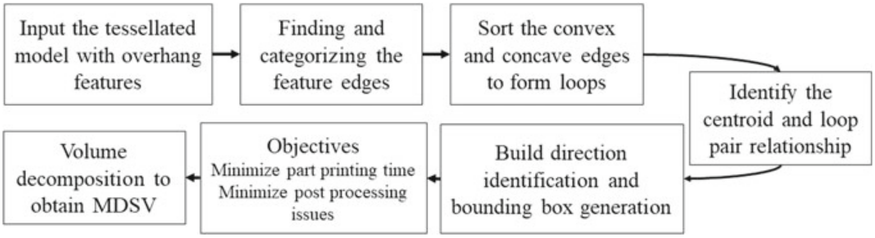


Fig. 3 Flowchart for volume decomposition of a part into MDSV

3.1 Feature Edge Identification

The common edge shared by two adjacent triangular facets is a feature edge, whose feature detection angle (θ) between the facet normal vectors should be higher than the threshold angle value. The threshold angle value was 10° or 20° between the adjacent facet normal [10] and it may vary for each tessellated model. Those feature edges above the threshold angle value form the boundaries of the model.

$$\theta = \arccos\left(n_i, n_j\right) \tag{1}$$

If the feature detection angle (θ) is equal to 0, then the triangles are in the same plane. If the angle value is greater than the threshold value, it is stored as feature edges.

3.2 Concave–Convex Edge Categorization

The collected feature edges are further categorized into concave and convex based on the angle information between the adjacent facet normal. Concave feature edges are identified if the facet normal of two adjacent triangles meet or intersect each other. The remaining edges are convex in nature and its facet normal between the adjacent triangles do not intersect each other. The attribute of an edge is classified into concave or convex based on edge classification angle ($\varnothing_{ab}$) information [10], which represents the angle between the facet normal of the two adjacent triangular facets.

$$\varnothing_{ab} = \left(n_i \times n_j\right).\overrightarrow{ab} \tag{2}$$

If the edge classification angle ($\varnothing_{ab}$) is less than zero, then those edges are concave in nature. And if the same angle value $\varnothing_{ab}$ is greater than zero, the edge is a convex edge. After categorizing the edges of the features into concave and convex edges, loops are generated by connecting the vertices of the concave or convex edges through the head–tail relation. The average of the edges' vertex coordinate value represents the loop centroid for that particular concave or convex loop. This centroidal loop information is sorted based on the increasing Z-coordinate value for finding the build direction of that particular decomposed sub-volume.

3.3 Build Direction Identification

In this study, all the concave loop normal direction was always pointing out from the tessellated model and the convex loop normal direction is pointing to the material side. The build direction vector is a unit normal in the form of directional cosines represented as $\hat{n}_i(\cos\alpha, \cos\beta, \cos\gamma)$. This vector is calculated for all sub-volumes decomposed within the bounding box of the concave and convex loops.

$$\hat{n}(\cos\alpha, \cos\beta, \cos\gamma) = \left(\frac{\hat{n}_1 + \hat{n}_2 + \hat{n}_3 + \hat{n}_4 \cdots + \hat{n}_i}{i}\right) \tag{3}$$

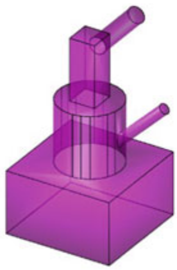
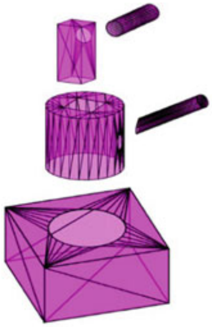
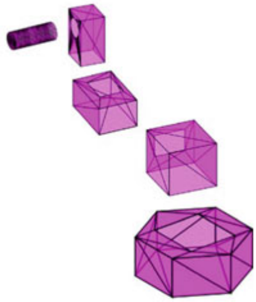
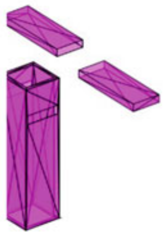
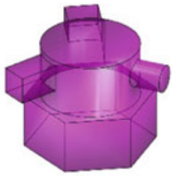
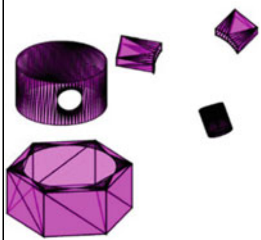
The coordinates of the concave loop, which is used for decomposing the sub-volume, contain the base planar surface (minimum coordinate) of the bounding box. The coordinates of the convex loop of that particular decomposed sub-volume provide the maximum Z-coordinate of the bounding box. This approach constructs the bounding box for all the sub-volumes to be decomposed with reference to a particular concave loop. The triangular facets within the bounding limits are collected for decomposing the part into sub-volumes. This procedure is repeated by making use of all the paired loops for the decomposition of sub-volumes.

3.4 Multi-directional Sub-volumes Decomposition

The convex-convex loops are paired for a non-overhang feature and concave-convex loops for decomposing the overhang features. The sub-volumes are decomposed from the tessellated model using the bounding box principle. Table 1 shows the test parts used in this study to validate the volume decomposition algorithm.

The part deposition time and average surface roughness (Ra) for the test parts using three-axis CNC systems and multi-axis robotic systems are compared to analyze the time reduction. Figure 4a shows the comparison results of the print deposition time in the UDD calculated using Ultimaker CURA software and MDD calculated for MRCME systems in RoboDK software.

Table 1 Test study parts and its volume decomposition results

 **Test part 1**	 **Volume decomposition results**	 **Test part 2**	 **Volume decomposition results**
 **Test part 3**	 **Volume decomposition results**	 **Test part 4**	 **Volume decomposition results**

4 Results and Discussions

The results of the volume decomposition algorithm provide the sub-volumes, which can be printed in a UDD technique. Decomposition of the parent volume into unidirectional sub-volume and joining the child sub-volumes to the parent sub-volume is a tedious process. In such a case, this sort of multi-axis part printing with robotic systems provides a better solution to print parts without or minimum supports and less part printing time. Figure 5a, b shows the assembled and disassembled universal coupling (case study part) to validate and analyze the results of the developed volume decomposition algorithm.

Support structures are needed to print the part 1 and part 2 of the universal coupling at any orientation. Hence, the volume decomposition of the parts as shown in Fig. 6a–c and printing using MDD systems is the best solution. This sort of part printing also addresses the bonding issues with the decomposed sub-volumes.

Process planning for part printing the decomposed sub-volumes involves filling the holes in the decomposed region, multi-directional slicing, and path planning [11]. The path plan information is converted to trajectory information using the inverse kinematics principle. The generated trajectories are simulated in a virtual simulation environment prior to part printing using RoboDK software. Figure 7a shows the

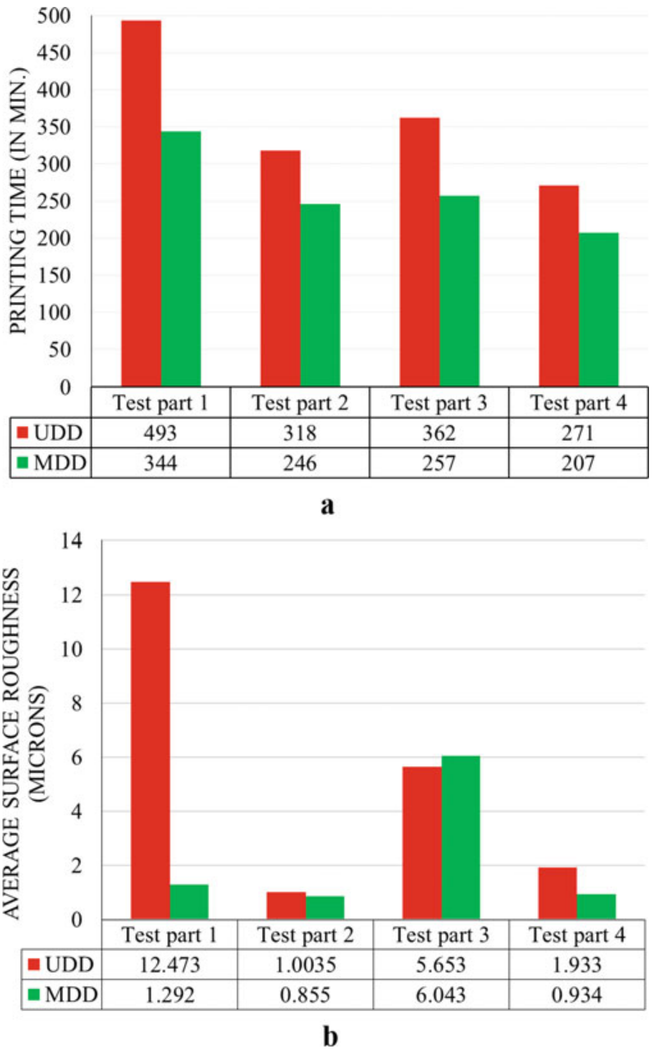


Fig. 4 **a** Comparison of print time using three-axis CNC and MRCME systems. **b** Comparison of measured average surface roughness in the OSV

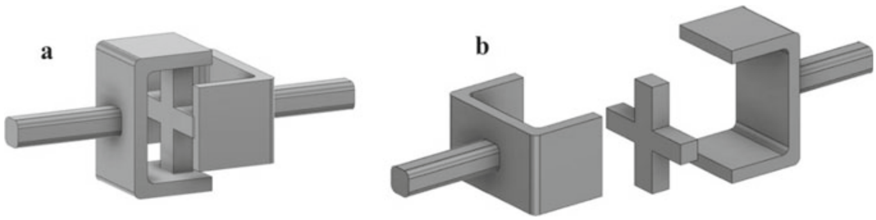


Fig. 5 **a** Assembled industrial universal coupling, **b** Exploded view

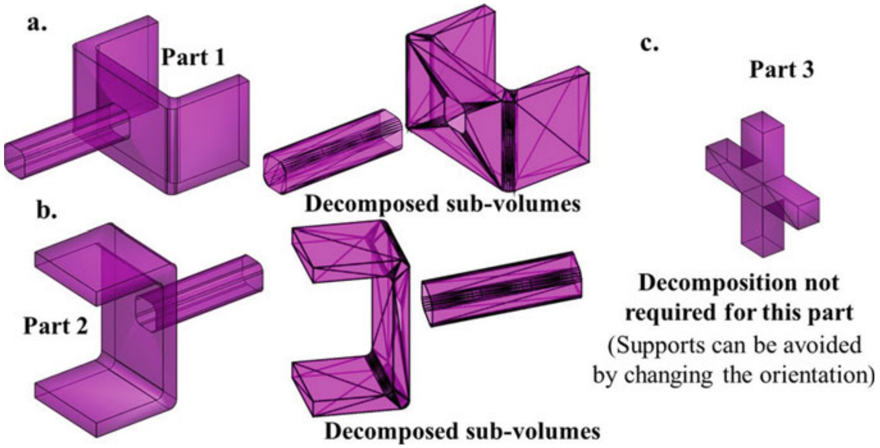


Fig. 6 **a** Decomposed MDSV of the one part of a coupling, **b** Decomposition results on another part of the coupling, **c** Central part

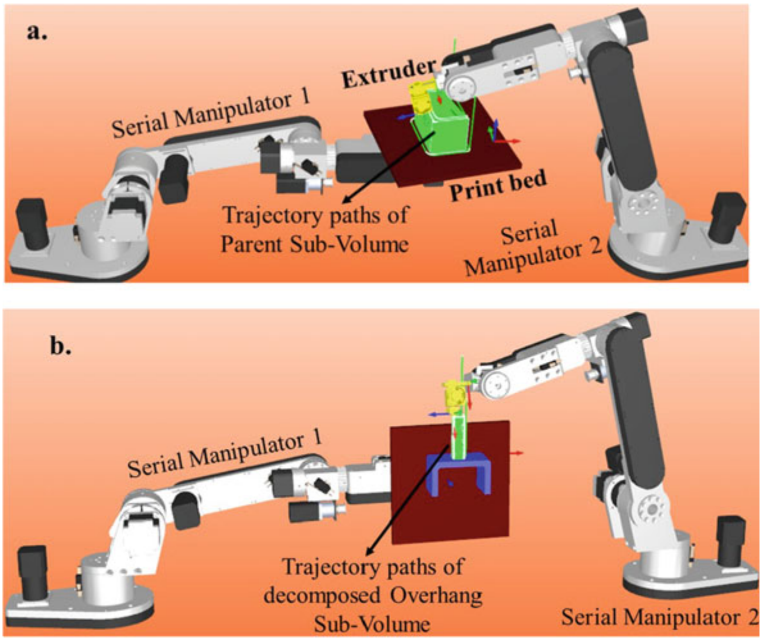


Fig. 7 **a** Virtual simulation of the trajectory paths of decomposed universal coupling. **b** Trajectory paths of decomposed overhang sub-volume

Table 2 Print time and surface roughness in the MDSV of case study part

		Part 1	Part 2	Part 3
Print time (min.)	UDD	876	876	189
	MDD	298	298	178
Surface roughness (μm)	UDD	18.36	19.54	7.24
	MDD	6.52	5.85	6.98

trajectory simulation of the parent sub-volume and Fig. 7b shows the trajectory information of the decomposed sub-volume printed by orientating the end effector at certain angles as per the build direction angle information using dual six-axis serial manipulators.

The robot control instruction code obtained is tested with the actual dual six-axis serial manipulator-based material extrusion systems in the future. Table 2 compares the print time with MRCME and CNC-based 3DP systems and surface roughness in the case study part.

The dual six-axis open-source serial manipulators shown in Fig. 8 have been fabricated by the authors to validate the results of the volume decomposition algorithm. These robotic systems have a payload of 2 kg and an accuracy of ±0.1 mm, which is the printing accuracy for the material extrusion processes.

Further, the integration of dual-six-axis robotic control for collaborative part printing through a graphical user interface (GUI) is under development for using the algorithms for material extrusion systems. Thus, this solution paves the way for automated hassle-free part printing in multiple build directions without the usage or minimum use of support structures.

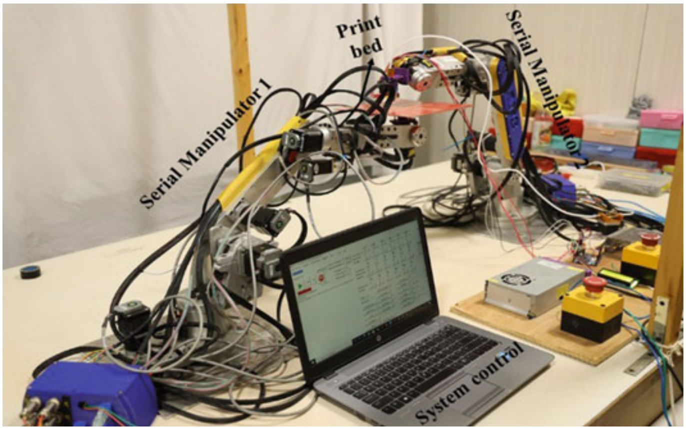


Fig. 8 Multi-robots collaborative material extrusion systems

5 Conclusions

This paper presents a methodology to decompose the faceted models for the part deposition using multi-robots collaborative material extrusion system. Identification of the feature edges is carried out by considering the threshold angle information, which may vary as per the accuracy of the tessellation. Multi-axis feature of a part was identified by recognizing the concave and convex loops from the tessellated model. In addition, concave-convex loop pair relation and bounding box techniques are used for volume decomposition. Nozzle collision-related problems and build direction identification of curvature-based features need to be addressed in the future. This work can be extended to metal-based DED systems to overcome the overhangs-related challenges associated with CNC-based DED systems.

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Digital Manufacturing

Optimum Scheduling and Routing of Material Through Computational Techniques

Pratik Mahesh Suryawanshi

1 Introduction

The scheduling problems can be modelled into virtually innumerable problem types [2]. Thus identifying the correct problem definition is as important as having an impeccable solution for the problem under consideration. The annals in operations research have suggested various solutions for scheduling and routing problems based on their area of execution and demand of the application. Modern production scenario has moved on to agile manufacturing and just-in-time manufacturing practices where every minute change in the process reflect on the final outcome of the production house. Thus, the objective of scheduling and routing is not to finish the activity in a minimum possible time but at the right time, where neither the activities lag nor it leads to the planned schedule. There are various practices adopted by the industry for this task which involves stern planning, careful execution and sustainable outcome. Over the years the computation has developed a human-like execution capability, which involves decision-making and trend prediction, and such computation based on large statistical data primarily known as artificial intelligence has promised the potential to augment the digitization of human culture [14]. The fourth industrial revolution expects vertical as well as horizontal communication to occur on such a level that virtually every unit of the system communicates and feedbacks everything. In such a scenario, traditional techniques tend to stall the outreach of modern principles which primordially are caused due to the mainstay of these techniques. The fourth industrial revolution is characterized by 'data collection' and 'data analysis', which is completely different from the second or third industrial revolution. In both of these scenarios, 'data' is not priorly concerned over other production aspects. These modern demands of the industrial revolution can be coped up with by amalgamating them with computational techniques which are characterized to operate

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effectively with these requirements [3]. At the human level, it is not possible to process this large data and that too simultaneously. Thus, considering these points a schema was brainstormed that would consolidate all the needs of the industry without compromising the current system. The proposed solution was the development of a computational program by the development team that would aid the supply chain and production management team in their daily and overall scheduling and routing problems. These computational techniques can study large data in a very short time and provide optimum solutions with a fair acceptance rate, thus reducing the workload of managers so that they can focus on uncertainty management. The data from the company was first identified and then modelled into a mathematical model which was subjected to constraints so as to gain the desired outcome.

2 Scheduling and Routing Techniques

Initially in the company, no specific scheduling or routing technique was used. The sole work was done by the experienced supply chain and production managers who used to macro and micro plan the production. Thus, the initial task performed was analysis and identification of a suitable technique that can be effectively applied. After studying various traditional techniques [2, 10] it was proposed that these techniques with certain modifications can be implemented in the company as an algorithm that would automatically compute the schedule and aid the activity in the company. Total tardiness was the principal method used to model the problem which was further enhanced by other optimization techniques. The apparent tardiness cost (ATC) minimization model was also considered to avoid earliness in production. The heuristic method as elaborated [6] was first used to find the coefficients; later mixed integer programming model was designed which describes the objective function subject to the greedy randomized adaptive search procedure (GRASP) which selects feasible solution from the set of best-restricted candidate list (RCL), out of which a random set is selected again to perform a local search with small changes in the solution to find the better value of objective function [8]. This aided the macro-level scheduling while the micro-level scheduling which included consideration of single machines, operating parallelly with some being identical and some not, was modelled with best-suited methodologies [1] with release date consideration [4]. For the sake of computation, algorithms were developed [5, 15], which were first written as pseudocode and then programmed. Following are the analytical treatments applied to develop the objective function, constraints and map them to the company's variables:

m = Machine number (0,1,2…i)

m = 0,1,2,3,4,5; where 0,1,2,3 are CNC and 4,5 are VMC

j = Jobs or batches (0,1,2…n)

j = 0,1,2,3,4,5,6,7,8,9

B = Big positive number

l = Position in sequence (0,1,2…n)

d_j = Due date of batch j

p_{ij} = Processing time of batch j on machine i

w_j = Weight of batch j

X_{il} = 1 if job is in sequence L, otherwise 0

S_{ij} = Starting time of job j on machine i

C_{ij} = Completion time of job j on machine i

T_j = Tardiness of job j

Thus, the objective function would be Eq. (1)

$$\min \sum w_j T_j \tag{1}$$

subjected to

$$C_{ij} \geq S_{ij} + d_j$$
$$S_{(i+1)j} \geq C_{ij}$$
$$S_{ij} + \left(1 + X_{j(l+1)}\right) * B \geq C_{im} - (1 - X_{ml}) * B$$
$$T_{ij} \geq C_{ij} - -d_j T_j \geq 0$$
$$S_{ij} \geq 0$$

3 Software Development Through Python and XML

Based on mathematical models, the most feasible programming language that would satiate the requirements was python because of its cross-platform support, number of open-source libraries and future scope to comply with the Industry 4.0 ready machine learning and deep learning systems. Python (3.9.5) was used in the development of this algorithm. The machine used for this program development is an Intel® Core™ i3-7100 @ 3.6 GHz, 4 GB RAM @ 2400 MHz, Intel® HD Graphics 630 operating on Ubuntu (20.0.4 LTS). The programming is compiled by its default command line-based compiler and typed in gedit. The programming went through standard stages of develop-deploy-test-redefine based on the outcomes observed [11]. Several versions with different features were tested and released out of which the best suited and applied is elaborated in this research piece.

3.1 Libraries Deployed

The primary need was the provision to define and solve the linear programming which was enabled by deploying the library ‘mip’. The eminent features of the mip are the ability to solve highly complex linear models, model the system in higher language, dynamic header loading, multiple solvers and such to note [12]. The scheduling model based on Eq. (1) along with its variables and constraints was constructed in mip and CP-SAT solver was used to provide the first possible optimization solutions.

As the data on the shop floor is neither static nor constant, thus it gave channelization in the direction of dynamic modelling and data analysis. This requirement was fit as a solution provided by the ‘Google OR-Tools’. OR-Tools is an open-source python library that provides combinatorial optimization with the help of a Glop solver. ‘Glop’ has its own set of assumptions which compulsory are subjected to the algorithms for which it is subjected to. The dominant feature of this library and solver is its dynamic data handling range and the ability to provide the best solution out of a very large set of possible solutions [9]. This library is not limited to classic linear programming problems but can also be coded as per the user’s need for further flexible computation by enhancing the source code provided by the developers.

After the successful trial of the mathematical model, the challenge was to develop a user-friendly U.I. and a platform so that the algorithm can be accessed with minimum effort. For this, the ‘tkinter’ library was used, which is a standard GUI development library accompanied by python [7]. Using tkinter, a simple GUI was designed considering ergonomic factors which are as demonstrated in Fig. 2. Further, the ergonomic enhancement included eliminating the need to run the algorithm by compiling and executing it. Thus, an executable was compiled which would suit both Linux and Windows operating systems using a very simple yet elegant library called ‘auto-py-to-exe’, which with minimal efforts produces the executable from desired python script with a bundle of interesting accessories like icon selection, standalone execution and so on [13].

3.2 Data Collection and Handling

It is a general practice that the data required in an industry is mostly stored and handled in Microsoft Office Excel. Task-specific spreadsheets are prepared accordingly which have the production capacity, deadlines and such related data specified. The schedule under analysis is for the 14th and 15th week of the year 2021. This is the time period under consideration because this program is developed in the 11th and 12th week of the year 2021. This time span also has a fixed deadline as the 21st week of the year 2021. Thus, in order to check the program’s effectiveness and compare it with the current system, the stated schedule plan was selected as it is and almost immediately executed. The major constraint here was the format in which the data was stored. The company has an integrated ERP software which maintains data pertaining to related processes such as cycle time, batch quantity, sequence of operations and so on, as represented in Table 1.

Using the data extracted from the ERP and considering the batch dispatch required, the time analysis was performed which yielded Table 2. In this table the actual inputs which are to be given to the program are determined based on general computation and are expressed as below. The selection of a particular machine for a specific job is decided based on the capacity, possible setting and operator availability for the scheduling time under consideration.

Table 1 Raw data extracted from ERP

Batch number	Part number	Process sequence and execution time (minutes)					
A0	4550	CNC Setting	CNC Operation	VMC Setting	VMC Operation		
		150	19	120	17		
A1	4550	CNC Setting	CNC Operation	VMC Setting	VMC Operation		
		150	19	120	17		
B2	1730	CNC Setting	CNC Operation	CNC Setting	CNC Operation	VMC Setting	VMC Operation
		70	11.5	70	9.5	90	10.5
B3	1730	CNC Setting	CNC Operation	CNC Setting	CNC Operation	VMC Setting	VMC Operation
		70	11.5	70	9.5	90	10.5
B4	1730	CNC Setting	CNC Operation	CNC Setting	CNC Operation	VMC Setting	VMC Operation
		70	11.5	70	9.5	90	10.5
B5	1730	CNC Setting	CNC Operation	CNC Setting	CNC Operation	VMC Setting	VMC Operation
		70	11.5	70	9.5	90	10.5
C6	4700	CNC Setting	CNC Operation	CNC Setting	CNC Operation	VMC Setting	VMC Operation
		70	15	70	7	80	20.75
C7	4700	CNC Setting	CNC Operation	CNC Setting	CNC Operation	VMC Setting	VMC Operation
		70	15	70	7	80	20.75
C8	4700	CNC Setting	CNC Operation	CNC Setting	CNC Operation	VMC Setting	VMC Operation
		70	15	70	7	80	20.75
D9	0270	CNC Setting	CNC Operation	VMC Setting	VMC Operation		
		120	25	120	20		

Table 2 Machine number and operation time (minutes) for respective batches

Batch number	Machine for operation 1	Operation 1	Machine for operation 2	Operation 2	Machine for operation 3	Operation 3
A0	0	3304	4	2942	NA	NA
A1	0	1119	4	987	NA	NA
B2	1	1025	2	859	5	962
B3	1	1094	2	916	5	1025
B4	1	576	2	488	5	552
B5	1	450	1	384	5	437
C6	3	2665	2	1281	4	3670
C7	3	1690	2	826	4	2321
C8	3	2230	2	1078	4	3068
D9	0	1495	5	1220	NA	NA

This data was then extracted to Excel spreadsheets in raw form. This data in raw form did not have a peculiar format or structure. Thus, a generalized format was proposed as shown in Fig. 1, which was maintained across the departments pertaining to this research. The data required for analysis is maintained in the Excel files, which was first condensed down to required variables. The data corresponding to variables under consideration was then exported into a comma-separated values (.csv) file for the sake of ease of data handling for the program. The .csv files can be opened in any text editor or an office Excel handler, thus the need for another data handler was eliminated without compromising the effectiveness of the code. The extracted scheduling .csv file is given as an input to the program through its navigation panel.

	Operation 1		Operation 2		Operation 3	
Batch 1	Machine Number for Operation 1 of Batch 1	Time to be consumed by Operation 1of Batch 1	Machine Number for Operation 2 of Batch 1	Time to be consumed by Operation 2 of Batch 1	Machine Number for Operation 2 of Batch 1	Time to be consumed by Operation 3 of Batch1
	Operation 1		Operation 2			
Batch 2	Machine Number for Operation 1 of Batch 2	Time to be consumed by Operation 1of Batch 2	Machine Number for Operation 2 of Batch 2	Time to be consumed by Operation2 of Batch 2		
	Operation 1		Operation 2		Operation 3	
Batch 3	Machine Number for Operation 1 of Batch 3	Time to be consumed by Operation 1of Batch 3	Machine Number for Operation 2 of Batch 3	Time to be consumed by Operation 2 of Batch 3	Machine Number for Operation 3 of Batch 3	Time to be consumed by Operation 3 of Batch 3
	Operation 1					
Batch 4	Machine Number for Operation 1 of Batch 4	Time to be consumed by Operation 1of Batch 4				
	Operation 1		Operation 2		Operation 3	
Batch 5	Machine Number for Operation 1 of Batch 5	Time to be consumed by Operation 1of Batch 5	Machine Number for Operation 2 of Batch 5	Time to be consumed by Operation 2 of Batch 5	Machine Number for Operation 3 of Batch 5	Time to be consumed by Operation 3 of Batch 5

Fig. 1 Standardized format for data collection and handling

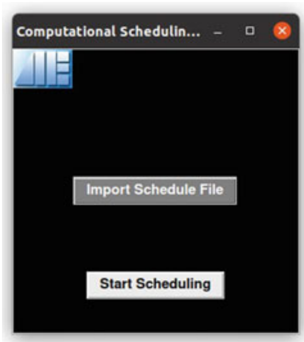

Fig. 2 Application user interface

The data from the scheduling file is imported into the algorithm in the form of a multi-dimensional array, and on those arrays the computational constraints are applied to get the best possible outcome (Fig. 3).

3.3 Sample of Code Deployed

The process of development is continuous which implies that there is not a confirmed or final version but the most acceptable outcome is considered to be standard and thus is elaborated further in this paper.

3.3.1 Pseudocode

```
Start
Input Selection
      Input "schedule.csv into program" with ',' as de-
      limiter and '/n' as end of line
Processing Input
      Len = number of lines in schedule.csv file
      Map input as tuple for 'Len/2' with ',' as sepa-
      rator
      Save as data frame
Assigning Variables
      Assign Machine Id(mid) to every first term of tu-
      ple
      Assign  Process  Time(duration)  to  every  second
      term of tuple
```

```
        If third term present:
              Append as deadline(dl) in tuple entry on
        (task_id)
        Assign Process Start Time (start_var)
        Assign Process Completion(end_var)
              Assign number of tuples as operation se-
        quence(task_id)
        Assign number of Len as number of batches(job_id)
        Assign batch number as Len changes
        all_tasks = {List of lists[job_id, task_id]}
  Algorithm
        For every task:
              end_var - start_var = duration
        Precedence for no overlap:
              For all [job_id, task_id + 1].start >=
              all_tasks[job_id, task_id].end)
              No overlap: If (job_id[1],
              task_id[1].start_var <= (job_id[2],
              task_id[2]).start_var for mid[1]==mid[1]:
              [start_var[1] + duration[1] <=
              start_var[2]]
        Deadline Constraint:
              For all [job_id, task_id].end_var <=
              [job_id, task_id].dl
        Objective Function:
              For all minimize[sum[task_id.duration]
  Display the most minimum outcome in command line
  File Outputs
        Create and write data in text file
        Open schedule.xml file
        Append the solution to corresponding variables
  END
```

3.3.2 Final User Interface and Deployment

Following is the simplified app UI. It has two options, the one on top to import the schedule .csv file while the below one starts the scheduling when clicked.

After selecting the CSV file containing the scheduling data in the required manner, ‘Start Scheduling’ is clicked on the U.I. after which the algorithm computes the shortest possible cycle time for given inputs. This output is displayed in the command line interface (C.L.I.) as shown in Fig. 3. Also, the schedule is produced as a text file output which is created by the program and saved in the program’s directory.

Further, this schedule obtained is used to edit a .xml file present in the same directory which produces the Gantt chart, a very vital tool for floor level reference and analysis. Here the variables are appended as ‘Component ID [batch number, operation number]’. This .xml file can be opened using Project Libre or Microsoft Project and shows the output as represented in Fig. 4.

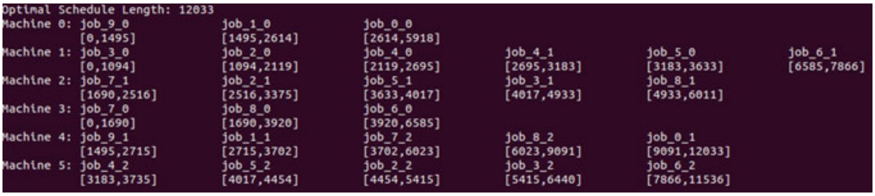

Fig. 3 Schedule output in the terminal

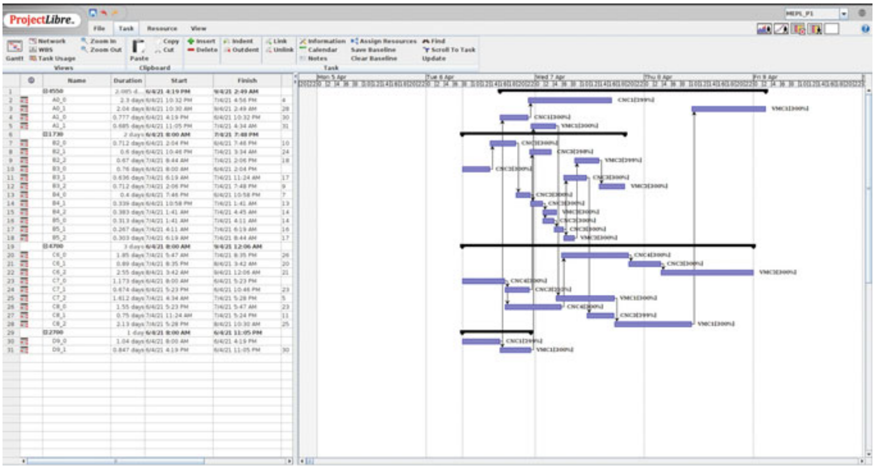

Fig. 4 Optimized scheduled as displayed in project Libre

4 Results and Discussion

The company currently uses a critical ratio and shortest delivery time first scheduling assisted by manual insights of the managers. This technique is used by assigning an algorithm to the Excel sheet. Following is the algorithm and its result applied to the schedule under consideration:

```
  Get Today (start); Batches' process durations (bdu);
Batches' deadlines (bdl)
  For n iterations (n = 1,2,3… = batch number)
  1st Iteration:
      C.R. = (bdl-start)/bdu for all Batches
      (C.R.)least1 = Batch Priority
      For respective batches:
      (bdl) - bduleast1 = (bdl)1
      (bdl)1 = new deadline for respective batch
```

Table 3 Critical ratio-based scheduling result

Batch number	Priority	Duration (min)
A0	3	6246
A1	7	2106
B2	8	1884
B3	5	3035
B4	9	1616
B5	10	1271
C6	1	7616
C7	4	4837
C8	2	6376
D9	6	2715
Total	**–**	**37,702**

Based on the above old algorithm, the following results were obtained by the production department, as shown in Table 3.

This technique lacks the consideration of parallel machining; thus, it was a manual task for the production department to assign duty to every machine for the next couple of days, every day after the second shift ends (16:00 h) by filling individual plan sheet on every machine. This task consumed their productive time to do similarly repeated tasks every day that too with less effectiveness. The scheduling activity is proposed by Mr. Surve (Production Manager, Marvelous Engineers Pvt. Ltd.), who proposed a schedule of 17,280 min considering parallel machining and routing as per his experience and manual problem-solving. For our schedule under consideration, he instructed us to consider a 25% lag in the schedule given by the new algorithm due to the uncertainties like power cuts, accident like such. These results have been condensed in the conclusion part which elaborates the effectiveness of this new algorithm.

5 Insights and Conclusion

The algorithm suggested that all of the input work can be finished in 12,033 min. When this is compared to the manual schedule designed by Mr. Surve which is 17280 min, there is a 30% time-saving in scheduling. If we consider a 25% lag in the programmed schedule due to uncertainties as per instructions, we still get 13.11% time-saving in the total schedule which is 2266 min. This time-saving is vital in production as it directly indicates the monetary benefits obtained. When the schedule was actually deployed on the floor, it was observed that 2357 min (13.64%) were saved as compared to the old scheduling technique. Also, this program takes parallel machining and deadline computation into consideration.

The algorithm has a major constraint of overlooking real-time scenario on the machine floor which can be eliminated by using machine learning which would identify and modify the inputs and algorithm accordingly. Further, IoT would enable real-time GUI-based scheduling as it would upload data, and at the same time, the data would be processed. Also, IoT would completely eliminate the need for manual data handling and would thus further rectify the SCM department's activities.

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Design of a Common Bulkhead Dome for Cryogenic Stage

Yogesh Pratap Singh, Pratik Tolambiya, Kshitij Sharma, Piyush Yadav, Soumya Subhrajita Mohanty, Harjit Singh, Suraj Kumar Mukti, and A. K. Asraff

1 Introduction

In recent years, ISRO has been extensively working to improve its launch vehicle performance in terms of payload capacity. Along the same line, one such novel key technology can be the incorporation of a common bulkhead (CBH) tank [1–4] in the cryogenic stage of an Indian launch vehicle. The cryogenic stage in the current ISRO launch vehicle, GSLV MkIII, consists of two separate tanks for fuel (liquid hydrogen (LH2)) and oxidizer (liquid oxygen (LOX)) with a truss-type intertank structure [5] connecting them as shown in Fig. 1a. However, this configuration induces large, concentrated loads at the truss interfaces leading to local buckling [3, 5]. Also, in this configuration, components on the dome are left open to the aerodynamic flow and acoustic loads [3]. Arunima et al. [5] suggested a closely stiffened intertank structure, as shown in Fig. 1b, with a provision for radial sliding to overcome the aforementioned problem. This solution suffered a mass penalty of about 100 kg as compared to the previous truss type. As a remedial measure, a CBH tank, as shown in Fig. 1c, was suggested in our earlier work [3], consisting of an initial design and analysis. A CBH tank utilizes a single tank with a common bulkhead separating two independently pressurized compartments containing liquid hydrogen (LH2) as fuel at 20 K and liquid oxygen (LOX) as an oxidizer at 77 K. Elimination of an intertank structure and an extra dome due to incorporation of a CBH tank will offer a significant mass saving. Any mass saving in the upper stage of a launch vehicle directly reflects in the enhancement of the payload capacity. Also, eliminating a

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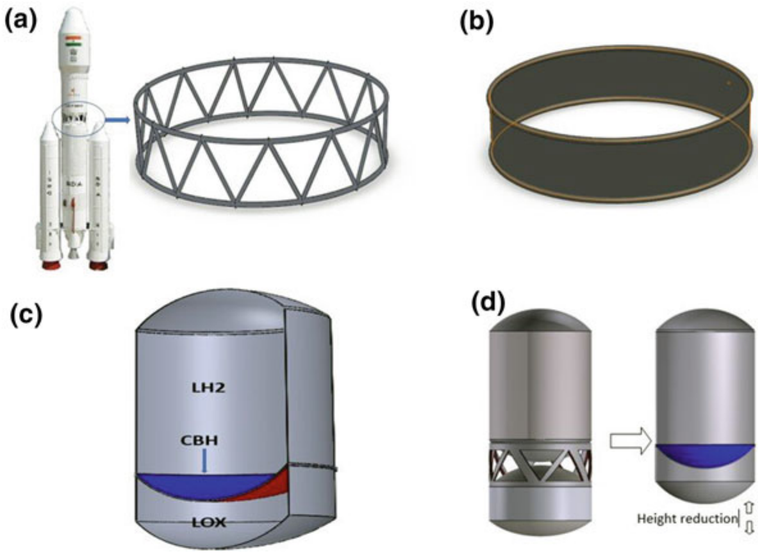

Fig. 1 **a** Truss-type intertank structure **b** Closely stiffened intertank structure **c** A CBH tank **d** Height reduction in a CBH tank as compared to a truss type [3]

2 m tall intertank structure leads to a reduction in the vehicle height, offering an aerodynamic advantage [3], as shown in Fig. 1d.

The major challenge in implementing a CBH tank is in the design and manufacturing of a CBH. The CBH is a common separation between the two cryogenic compartments. It must be designed against the design and thermal loads owing to a 57 K thermal gradient with minimum weight. MT aerospace [1] developed a sandwich-type CBH for Ariane 5 using an AIREX foam core sandwiched between two aluminum (Al) face sheets. NASA [4] used a similar concept but with a phenolic honeycomb core in SATURN S-II. Airbus Safran Launchers, Bremen [2], worked on the inner wetted thermal insulation (IWTI) concept where the polyurethane (PU) foam was in direct contact with a cryogenic medium. From a detailed study and our earlier works [3], we conclude that sandwich CBH is a better approach to CBH design than an IWTI approach. In general, a sandwich CBH consists of a core material sandwiched between two thin face sheets (generally Al). The thin sections have relatively little strength by themselves in a large dome. The CBH must be designed against design loads, reverse pressure, and heat fluxes with minimum weight.

However, to the best of our knowledge, a sandwich-type CBH with a foam-filled honeycomb core (FFH) is yet to be explored. The paper first presents a comparison between three types of core, i.e., a foam core (AIREX), a honeycomb core, and an FFH core. In terms of mass and space requirements, the solutions were in favor of an FFH core. The manufacturing feasibility of a sandwich-type CBH with an FFH core is derived after extending the studies from the other two. NDI techniques are also suggested for possible defects.

2 Design of a CBH Dome

The design of a CBH dome includes the design of the face sheets, core materials, and the end skirts joining the CBH dome to the external tank wall. The face sheets are assumed to be made to Al 2219 in all cases and designed with thin pressure vessel criteria. The core is designed for bucking against reverse pressure, inertia loads, other design loads, and minimum heat leak across the CBH. The Al face sheet being relatively conductive will be thermally transparent. We have considered a design load factor of 1.25 and a thermal FOS of 1.33 for the CBH dome design [3]. Both steady-state and transient thermal analyses are considered. The comparison points are discrete, keeping in mind the manufacturing feasibility, availability, and other constraints of the material being used. The shape of the CBH dome can be hemispherical or ellipsoidal, independent of the shape of the tank's dome. Since GSLV MkIII has a tank radius (*R*) of 2 m, CBH can have a radius equal to or above 2 m. The mass saving in the current GSLV MkIII [3] can be calculated by adding the mass of two toroidal domes and truss-type intertank from the previous configuration and subtracting the mass of the CBH. The minimum mass of CBH will correspond to the maximum mass saving. With Al 2219 as face sheet, sandwich-type CBHs with different types of the core are compared at different CBH dome radii using ANSYS® and shown in Table 1 and Fig. 2.

Table 1 Comparison between different core types in a sandwich CBH of $R = 2.5$ m (minimum mass point)

Core type	Foam core	Honeycomb core	Foam-filled honeycomb core
Minimum mass of CBH (including face sheet) in kg	193.022	223.997	187.853
Mass saving (GSLV MkIII) in kg	470.478	439.502	475.646
Core thickness (in mm)	62.5	73.0	27.2
Load factor (at min. point)	1.25	8.54	1.25
Thermal FOS (at min. point)	5.68	1.33	1.73

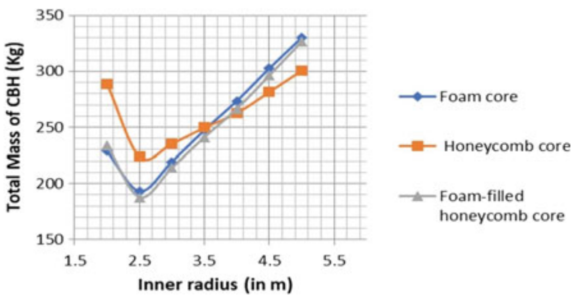

Fig. 2 Comparison of total mass for different core types with radii of the CBH

(A) Foam core

A reactor foam, i.e., AIREX R82.80, is considered to guarantee mechanical strength against the reverse pressure that was lacking in a spray foam [1]. From Fig. 2 and Table 1, the minimum mass corresponds to a CBH radius of 2.5 m with a load factor of 1.25, which governs the core thickness. The thermal criterion is automatically satisfied with a FOS of 5.68 due to the insulating nature of the foam.

(B) Honeycomb core

A HexWeb® HRH-10 phenolic honeycomb is considered with a 3.2 mm cell size due to its minimum conductivity among other available cell sizes because of the air convection phenomenon inside the cells. HRH-10-3.2-96 (density = 96 kg/m^3) was considered as it offers minimum mass at $R = 2.5$ m. Due to its relatively higher conductivity compared to AIREX, the thickness of the core is now governed by thermal criterion to limit the heat flux with a FOS of 1.33 (see Table 1). The load factor of 8.54 shows high strength of honeycomb material than required (1.25).

(C) Foam-filled honeycomb core

Learning from the above two cases, we can combine foam and honeycomb properties to avoid an overestimation by any of the criteria. In an FFH, the required strength to the core will be supplied by the honeycomb, and the foam material provides the needed insulation. Now relatively soft spray foams like PU foams can be used inside the cells, which have even better thermal insulation capabilities than AIREX. However, the overall density of the core increases, but the low thickness of the core (27.2 mm) minimizes the overall mass of an FFH core compared to the other two cores.

The overall conclusion for the above is that for GSLV MkIII, the CBH radius must be equal to 2.5 m (truncated shell) for any core type. Among the core, the minimum mass was obtained in the CBH core made of an FFH material. The slight difference between an AIREX core and an FFH core mass shoots further up to 17 kg at cryogenic temperatures. There is a significant mass saving with respect to the current GSLV configuration in all the cases; however, an FFH offers a maximum overall saving of 475.646 kg among them. The Al face sheet thickness for a 2.5 m radius dome was 1.3 mm, with a core thickness of 27.2 mm for the FFH core.

Hence, the above mass savings encourage us to focus on the manufacturing feasibilities of sandwich-type CBH, especially on one with an FFH core.

3 Manufacturing Feasibility

The first step is to freeze the cell structure morphology, chemistry, and compositions of Al alloys, core material, and all other materials using design and testing. The feasibility of the following processes is studied and discussed:

(a) Manufacturing of an Al face sheet dome from the sheet metal.
(b) Bending core materials and bonding them to a face sheet dome.
(c) Non-destructive testing (NDT) for defects at each stage.

3.1 Manufacturing of an Al Face Sheet Dome from the Sheet Metal

Aerospace Al alloys are generally used as face sheets (Al 2219 in our case). Rolling is widely used commercially to manufacture a sheet metal from billet because it is an economical process that provides a high degree of uniformity and has lesser scope for defects. The transition from a sheet to a complete curved dome (in our case, a dome of radius 2.5 m and truncated at 2 m radius) can also be done by joining several parts in the form of petals [4], as shown in Fig. 3a. Several processes that can be used for the operation of sheet metal to dome manufacturing are compared based on some influential factors, as shown in Table 2. Color codes (at the bottom) have been used according to the performance of each process with respect to corresponding factors for better visualization. The conclusion is derived with the help of these color codes.

From Table 2, *spin forming* was found to be most appropriate for manufacturing the dome from Al sheet metal, followed by *shot peening*. Shot peening, however, requires milling and grinding for the final shape. Stretch forming is useful in case petals have to be made for dome manufacturing, as shown in Fig. 3a.

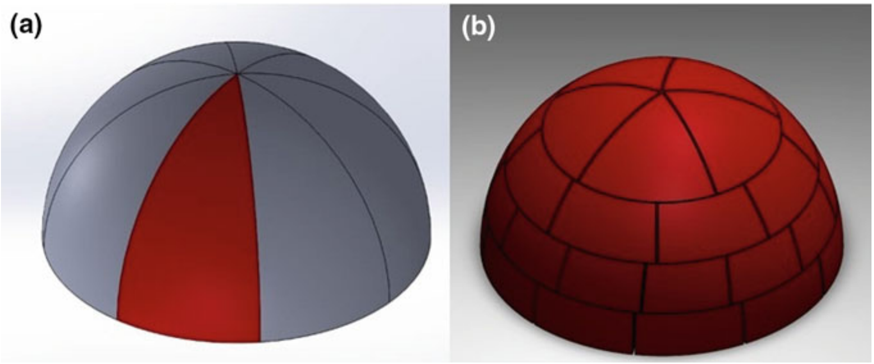

Fig. 3 **a** Dome made up of petals, **b** Core made up of bent tiles/panels

Table 2 Comparison of different possible processes for dome manufacturing from Al sheet

Process	Mechanical properties	Formability	Surface finish	Tolerance (final dimension)	Economy
Explosive forming [6]	Not much change (YS, UTS)	Formed with very little difficulty	Good	Working tolerance is 0.01 inch	Cost of facility is low but labor cost per part is high
Spin forming [7-8]	Increases 2-2.5 times	Low forming load; very good	Good	high accuracy (ideal for our *R* and *T*)	Low tooling cost for large parts
Hydro forming [9-10]	Improves buckling strength	good	Good for inner surface only	Inconsistent thickness obtained	High cost
Shot peen forming [11-13]	Improves (reduces probability of crack initiation)	Very good	Bad but improves with grinding, milling	Consistent (for curves within elastic range)	Low, as it is a die-less process
Stretch forming [14-15]	Increases (YS, tensile strength)	Good	Better shape control, surface quality	Thinning of sheet (allowance needed)	Low cost
Incremental sheet forming [16-18]	Increases (YS, tensile strength)	Low forming force	Poor surface finish	Non uniform thickness	Low cost
YS= yield strength, UTS= ultimate tensile strength, *R*= radius, *T*= thickness					
Rejected	Not favorable	Neutral	Favorable	Very favorable	

3.2 *Bending Core Materials and Bonding Them to a Face Sheet Dome*

Once the face sheet dome is ready, we need it to bond it with a core material of specific thickness in between them. We will present the bending techniques for foam core and honeycomb core and extend this to the feasibility of an FFH core. The cores are made into small–small panels (not into petals or a complete dome) as shown in Fig. 3b and later joined together.

For a **foam core** (AIREX R82.80), *shaping* can be done by cold bending and thermoforming [19]. The thermoforming with an optimal heating condition and time is better than cold bending for an R82 grade AIREX. The pressure in this process can be applied in three ways [19]:

(a) Creep forming (application of weight)
(b) Vacuum forming (air evacuation)
(c) Compression molding

The bonding is done in two parts: first, it is trimmed and bonded to one of the face sheets with adhesive (epoxy resin) and then to the other face sheet employing a *resin injection method* using a low viscous epoxy resin [1].

For a Nomex **honeycomb core** of hexagonal unit cell, the unit cell loses its shape on bending, leading to a loss of strength. To reduce the chances of such distortions, it becomes necessary to use small panels (slight bend) [20], as shown in Fig. 3b. Small pieces can be *milled* to obtain a slightly bent contour and later arranged together to form an overall shape of the dome. For bonding it to face sheets, *epoxy resin* and *phenolic resin* at 80–130 °C can be used as an adhesive. Vacuum bagging and autoclaving can be used for bonding, preferably at higher temperatures for better chemical bonding.

A **foam-filled honeycomb core** with a Nomex honeycomb and a spray foam (PU) will offer more bending stiffness together and hence is difficult to bend. The solution to this can be bending small Nomex honeycomb panels as before, then filling spray foam into the cells, and finally trimming both sides for final dimensions. Epoxy resin can serve as a better adhesive for bonding as it can be used for both foam and honeycomb. However, experimentation is needed to give conclusive evidence to this study of an FFH core bending. ISRO has already been using a PU foam for external tank insulation in their launch vehicle.

3.3 Non-destructive Testing (NDT) for Defects

Due to the complexities in the design and manufacturing of a CBH dome, there are severe chances of defect generation. NDI methods are studied stage-wise in Table 3 for the identification of possible defects. Stage 1 includes NDI techniques used after face sheet dome manufacturing, stage 2 includes NDI techniques after foam/honeycomb/FFH core bending (before bonding to face sheets), and stage 3 includes NDI techniques after the combined sandwich structure is formed.

4 Results and Discussion

The CBH must be designed keeping in mind both the design and the thermal aspects. The dimension and cost of the actual setup are too high and difficult to meet at an academic level. The buckling design load depends on the exact dimensions and shape of the CBH dome, while thermal fluxes depend mainly on radial thickness. Hence, the thermal performance of the CBH can be judged on a scaled thermal setup by maintaining a 57 K temperature gradient. Therefore, our recent development

Table 3 Stage-wise NDI techniques

Stage	Name	NDI techniques	Defects (used for)
1	Spin forming, Hydro forming	Laser shearography [21]	Wrinkling
	Incremental sheet forming	Laser shearography [22]	Sheet thinning
	Shot peen forming	Laser shearography, magnetic methods, eddy current method, Thermography [21, 23]	Surface defects
2	Honeycomb and foam core bending (without face sheet)	Ultrasonic method [24, 25]	Core cracks, impact damages
		X-ray radiography [25]	Blown/condensed/corroded/cut out/crushed core, foaming adhesive voids
3	Sandwich structure (with face sheet)	Ultrasonic method [24, 25]	Core damage, fluid intrusion into the core, planar voids
		X-ray radiography [25]	Air gaps in filler adhesives, fluid intrusion into the core, core damages

includes fabrications of a thermal setup. A design setup where pressurization can be given by any available fluid other than cryogenics is in the planning phase, keeping in mind the cost of cryogenic insulation (external) for the whole setup. A coupled setup can only be used when a proper connecting interface/skirt between a CBH and the external tank wall is designed. In this case, the heat leak between the two cryogenics from corners can be minimized.

A scaled thermal setup, as shown in Fig. 4a, has been used to evaluate the heat flux associated with specific core thickness. This heat flux should be below the flux permissible limit specified for GSLV MkIII. The actual setup can be seen in Fig. 4b, where the two small tanks carry two different temperature liquids connected by a core of specific thickness. In an actual launch vehicle, the external insulation is achieved by a PU foam, while we have used a cost-effective cotton (a good insulator) for the same since external insulation is not our area of concern. This is required to ensure most of the heat flux through the face containing the core.

To evaluate the performance of the setup, AIREX (Trident foam Ltd, UK) was used along with hot and cold water differing by a 57 K gradient after the steady-state is reached (refer to Fig. 4c). The conductivity obtained with the experiment using the temperature sensors showed only 2% error at this temperature range, indicating the effectiveness of the setup for future use. The insulating performance of the core will further improve at cryogenic temperatures [1, 2]. For a particular thickness of the AIREX foam, a heat flux of 65.67 W/m^2 is obtained experimentally, which closely matches with the heat flux obtained through the finite element model/design (65.70 W/m^2). This setup can be used with different types of core materials and in

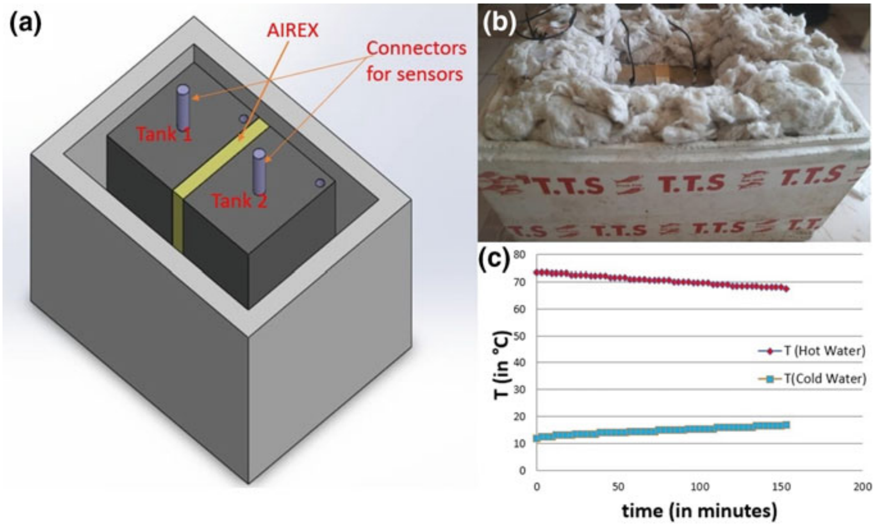

Fig. 4 **a** Thermal setup model **b** Actual thermal setup **c** Test results for two tank compartments

different environmental conditions (cryogenics) in the near future. Liquid LN2 will be preferred over LOX for safety reasons. Additionally, another thermal setup with a corner skirt is being planned to ensure minimal heat leakage through the corner connecting region.

5 Conclusion

This paper presents the design and manufacturing processes required to incorporate a CBH tank in GSLV MkIII over current technology. A sandwich-type CBH with a foam-filled honeycomb was found suitable in terms of mass and space (thickness). An overall mass saving of about 475 kg can be achieved using an FFH core. The CBH tank also eliminates problems encountered in the current truss-type intertank stage. Stage and component-wise manufacturing feasibility was discussed, along with their NDI techniques. Test results from our recent development of a thermal setup indicated its fitness for future use in varying environmental conditions and with different core materials.

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Implementation of Simulation Practices for Plant Optimization

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1 Introduction

Modern production is specified by a wide range of products for its variants, production costs, quick turnaround of new product launches, and the time duration between the design and launch phase. Continual reduction in the launch of the products and their variants due to strong competition and the changing requirements of the customers make the companies identify the enhancement areas in the production process and implement the changes as required to improve for quick turnaround. Changes in every production process allow for some limitations to the manufacturing capacity of the enterprise since the existence of a bottleneck is the main factor affecting the efficiency of the production line and management [1, 2]. The theory of constraints (TOC) assumes that every system has one basic limitation that influences the efficiency of the system in a given period [3, 4]. Elimination of bottlenecks in the process is the key issue of the system. Bottlenecks lead to various consequences. If the plant does not meet the market demand, there is a risk of losing the market share, and if the production exceeds, it incurs a lot of additional cost in terms of inventory, storage, and damage in a few scenarios.

A bottleneck is defined as a workstation limiting the production efficiency of the entire process [5]. Bottleneck at a particular station can lead to a situation in which a workstation before the bottleneck completes processing its task cannot move the

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semi-finished product to the next station due to the presence of a bottleneck in-between. Bottlenecks extend the cycle time of the process and decrease the throughput and have an adverse effect on the efficiency of the system.

It is very crucial to identify the bottlenecks in the process to improve the functioning of the workstations. Identifying bottlenecks in the system is the first stage of managing constraints according to the Theory of Constraints [4]. Eliminating bottlenecks at a few locations may lead to constraints at the new areas in the process. All these scenarios can be analyzed using various simulation software.

The case study consists of an automotive assembly line with three variants getting assembled at present and has future plans to incorporate three additional variants in the same assembly line which vary according to the geographical condition, domestic, and export demand. The greenfield plant with assembly lines foreseen issues during their plant facilities installation. Some of the issues identified are mentioned below:

- Plant layout and space utilization (greenfield)
- Futuristic variants and their projected volumes for the next three years
- Number of stations of the assembly lines (robotic/manual process)
- Assembly line processes of the different variants of the products
- Inventory management including material replenishment
- Resource management
- Cycle time/bottlenecks for the different variants of the product.

Considering the above-mentioned issues, plant simulation (digital manufacturing as a part of Industry 4.0) is carried out accordingly and the results from the plant simulation are analyzed to improvise the output through multiple iterations. Also, futuristic plans have been considered and simulated to identify the bottlenecks related to the above problems and can be addressed during the product design stage (concurrent engineering) which will help to minimize/eliminate all the concerns prior to the facilities installation and commissioning including proving on the shop floor.

Simulation software with a lot of computing capabilities increases the capacity of the simulations to project changes on the model before implementing any changes physically in the plant. It is necessary for companies to solve the increasing complex production scenarios. Virtual simulation helps in evaluating the different production of the product and its variants and their behavior, with which new strategies can be developed and implemented effectively without any production bottlenecks in the process and increase the productivity with minimum inventory level in the line.

2 Research Methods

Deep study on the existing process is essential to arrive at the methodology with which the real-time issues can be eliminated. Virtual simulation is a replication of the existing production system in the virtual space with the use of a simulation model. Simulation models are used to reduce the risk of failure while implementing significant changes to the existing system. The construction of a simulation model

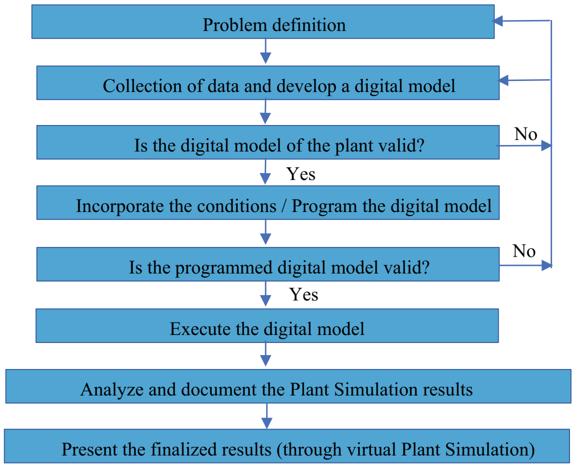


Fig. 1 Seven-step approach to conducting a successful simulation study [6]

is very difficult as it includes a lot of real-time data to develop. The model of the system represents its properties, features, and limitations. Upon generating the model, analysis is carried out to determine the required elements in the process. As a method, a computer simulation is a system of research activities, i.e., a structure of stage activities aimed at achieving a research objective. The creation of a simulation model of a process is a multi-stage task [6]. Figure 1 represents the seven-step approach to conducting a successful simulation study.

The application of simulation in production processes constitutes a form of experimenting with a computer model. Its objective is to determine how the production system will react to various changes according to the scenarios. Simulation models are used when it is very difficult to arrive at a solution, especially in the case of dynamic changes in the production system. The virtual simulation process ensures whether the undertaking is properly designed and is working in a proper manner. The simulation of the production process allows familiarizing with the functioning of the studied object and its analysis. Simulation helps in visualizing the process from a few minutes to the desired duration of the production cycle. It also allows the earlier detection of the issues that may cause problems in the production.

3 Case Study

A case study is carried out to analyze the foreseen issues which are discussed earlier regarding the variants getting assembled in the assembly line and bottlenecks associated with it in the production line. The case study includes problem definition, where all the issues are considered for the design of the digital model. Data regarding the assembly line right from raw material stores to finished products dispatch has been collected and the digital model is created accordingly. We need to remember that

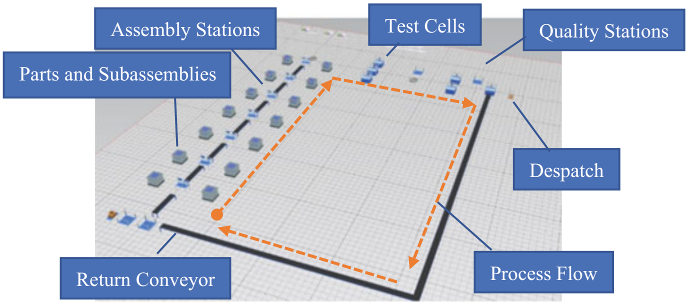


Fig. 2. 3D model of case study

creating a digital model of the layout is a very important criterion in the simulation process. The accuracy of the simulation depends on the quality of the model with different variable parameters which are simulated. The digital model is then programmed and the real conditions, such as material flow, process flow and its cycle time, stoppages, etc., are incorporated to resemble similar to the actual plant setup.

The case study as shown in Fig. 2 consists of a single flow process with seven workstations capable of carrying out assembly activities based on the variants, three test cells, and two quality stations. The assembly starts at station-1 and gets completed at station-7. The assembly then gets transferred to test cells based on availability. The tested assemblies are then transferred to the quality stations. Then the okayed assemblies are then dispatched and the process gets repeated. Assemblies which are failed at test cells and quality stations are moved to their individual repair areas and the rework activities are carried out.

The digital model is simulated using Tecnomatix Plant Simulation tool for various number of iterations and the results are captured. Deep analysis is done to identify the issues and the bottlenecks are minimized/eliminated accordingly.

4 Case Study Results

Based on the process flow, stations have been organized to reduce the material flow to the maximum. This has been achieved through various iterations for the different layout formations. A number of stations in the assembly line are also defined by analyzing the utilization of each station for the different layout formations and are automated to synchronize with the process flow to achieve maximum throughput. The best possible layout is as shown in Fig. 2, which is a single flow process.

Future variants are considered and the volumes for the next three years are incorporated in the digital model and simulated to analyze the throughput, utilization of each station, and the bottlenecks are minimized/eliminated to streamline the process. Station-7 cycle time has been optimized for line balancing.

Table 1 Case study cycle time details

S. no.	Parameter	Time (s)
1	Assembly station-1	126
2	Assembly station-2	137
3	Assembly station-3	132
4	Assembly station-4	126
5	Assembly station-5	144
6	Assembly station-6	126
7	Assembly station-7	173
8	Test cell 1	350
9	Test cell 2	350
10	Test cell 3	350
11	Quality station-1	150
12	Quality station-2	150
13	Dispatch	145

Bottlenecks in the material flow of the assembly line are analyzed and it has been observed that the replenishment of a few parts is done more frequently as they are used comparatively more than the other; hence its storage capacity has been increased at the line side. This has optimized the resource movements and also increased the availability of parts at the station. The replenishment frequency of the parts for the new variants has been streamlined and optimized so that material in the line is replenished every 3–4 h and some critical parts per assemblies will be just in time (JIT).

The model designed as shown above is fed by the data in Table 1 and is simulated.

During the simulation, the digital model has produced 21 assemblies per hour.

An initial analysis of the digital model states that assembly station-6 has the maximum blockage. Working, waiting, and blockage of the different stations are listed in Table 2.

The analysis of the statistics states that among seven assembly stations as shown in Fig. 3, assembly station-7 is used with a maximum working% of 96.82. This has created maximum blockage at station-6 with 23.18% and maximum waiting time is at station-4 with 16.29%. Test cells and quality stations do not have any blockages as shown in Figs. 4 and 5. Test cell 3 has a maximum waiting time of 27.38%, whereas working% in quality stations are equally distributed.

Identifying the bottleneck is the major task in the improvement of the process. In this case, the major bottleneck is at station-6 with a blockage of 23.18%, which needs to be addressed on a priority. During analysis, virtual simulation software allowed us to identify the bottleneck and steps to improvise the process, thereby the cycle time of station-7 is reduced to 144 s from 173 s and the simulation is carried out again to analyze the effect of change in cycle time in the complete process. It has been observed that the throughput is increased by 6.76%, i.e., from 21 assemblies per

Table 2 Statistics of the digital model

S. no	Station	Working %	Waiting %	Blocked %
1	Assembly station-1	74.23	16.14	9.63
2	Assembly station-2	80.21	10.15	9.64
3	Assembly station-3	94.38	4.59	1.04
4	Assembly station-4	72.94	16.29	10.77
5	Assembly station-5	82.93	4.74	12.33
6	Assembly station-6	71.61	5.21	23.18
7	Assembly station-7	96.82	3.18	0
8	Test cell 1	73.48	26.52	0
9	Test cell 2	73.29	26.71	0
10	Test cell 3	72.62	27.38	0
11	Quality station-1	41.88	58.13	0
12	Quality station-2	41.87	58.13	0
13	Dispatch	36.94	63.06	0

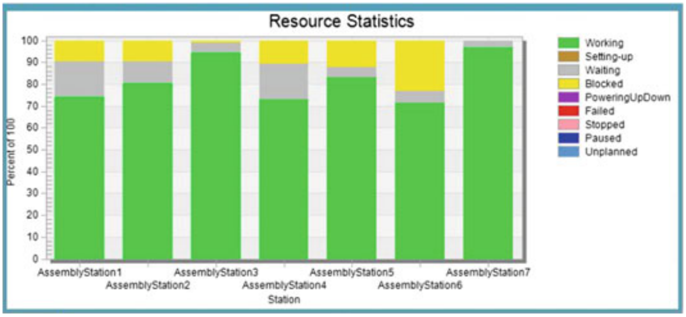
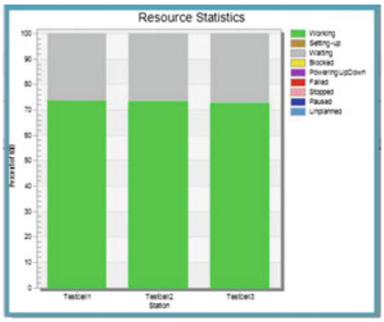


Fig. 3 Resource statistics of assembly stations

Fig. 4 Resource statistics of test cells



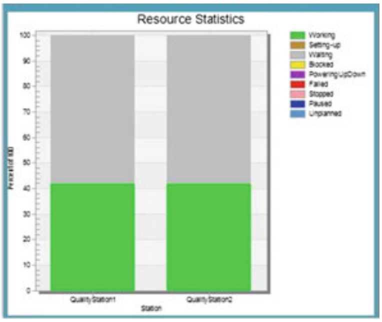


Fig. 5 Resource statistics of quality stations

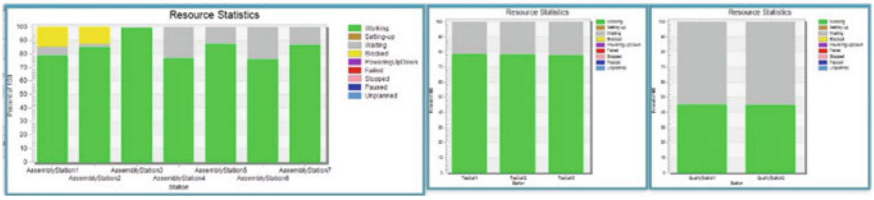


Fig. 6 Improvised resource statistics

hour to 25 assemblies per hour and blockage at stations 3, 4, 5, and 6 are completely eliminated, as shown in Fig. 6.

A total of 200 assemblies are produced per day against the requirement of 215 assemblies per day in a single shift, thereby optimizing the resources. If there is peak demand for the assemblies, the second shift can be utilized to meet the desired volumes.

5 Conclusion

The main objective in the case study is to find the issues related to plant layout optimization, future volumes based on demand, bottlenecks in the process flow, inventory management, and replenishment using a simulation tool. This paper explains the analysis and the ways in which the issues are addressed and the bottlenecks have been eliminated in the assembly stations by improvising the cycle time at station-7. With the help of the Tecnomatix Plant Simulation software and its conditional coding, the results will be close to the real-time scenario and help in visualizing the whole plant much before the implementation phase in order to meet the varying demands of the assembly products, thereby meeting the expectations of the customer.

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Industrial Application of Augmented Reality: Maintenance of Multi-process Robotic Cell

Shantanu Pabitwar, Vishnukkumar Sadagopan, Preeti Joshi, and Sunil Jha

1 Introduction

With the emergence of Industry 4.0, a new technology that shows significant results of increasing productivity in the industry is augmented reality (AR). AR is a new form of human–machine interface that overlays virtual data (computer-generated) onto real objects [1]. AR is a set of technology that overlays images and animations onto the physical world. AR has key capabilities like visualize, instruct and interact. The implementation of AR for training helps to understand the content of service manuals effectively and increases the efficiency of the users, which eventually reduces the cost of training. With the application of AR, the cognitive load on the user gets reduced and the chances of success get increased.

Furthermore, other researchers have identified other applications of AR in maintenance, diagnosis, training [2] and performance measurement [3]. Some of the studies showed the AR implementation in various aspects. Thus, AR can be useful for many situations in maintenance where the user needs additional information [4]. Many platforms were created to enable a product-service system to enable remote maintenance with the help of augmented reality and the cloud [5]. Furthermore, virtual and augmented reality have been extensively employed to instruct technicians in the

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performance of assembly duties [6]. AR reduces the cognitive load of the user which leads to the betterment of industry by increasing the productivity of the firm. With the changing pace of technology, there is a need to compete with competitors, and AR can provide a 10 × potential to move ahead in the race.

All the techniques used in AR are user-friendly and easily accessible to newly joined trainees, so with the use of AR, trainees will increase their chances of success and this study revolves around the maintenance by first-time users. Herein, this research presents a detailed explanation of how AR experience is created and how it is implemented at the IITD-AIA Foundation for Smart Manufacturing. The main objective of this paper is to provide maintenance guidance with the use of augmented reality. This AR experience involves step-by-step procedures and safety steps to ensure safety at the workplace. This AR experience is useful to train the users in a better way.

2 Methodology

The creation of AR experience involves a lot of steps to be carried out. To create this deployed AR experience, the steps involved and methodology adopted are presented in Fig. 1. This figure represents the way in which this research is carried out and finally implemented on multi-process robotic cell.

The prior search involves the study of the system to identify the critical station present in the system for implementation of maintenance. Further, AR experience is created for the critical station with the creation of 1:1 CAD of the systems and entities present inside the system. Animation is created for the identified maintenance activities which are then collaborated with the user interface of the AR framework. After setting the user interface AR experience is published, which is stored inside

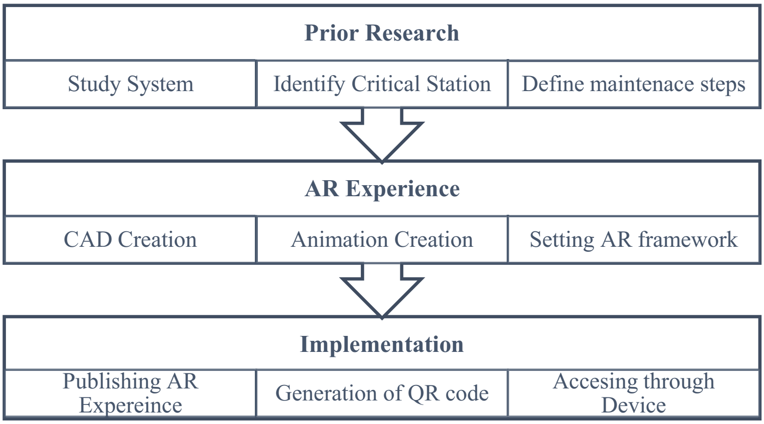

Fig. 1 Steps carried out in implementation

a QR code. This QR is scanned by the user with the help of a mobile device to get inside the AR experience.

This paper shows the actual implementation of AR at IITD-AIA Foundation for smart manufacturing (FSM) and the above-mentioned methodology is carried out on a multi-process robotic cell situated at FSM.

2.1 Need of Maintenance and AR

Maintenance is the core activity of the product lifecycle as it accounts for 60–70% of the total cost [7]. This has led to the high demand for maintenance planning throughout the product lifecycle and the involvement of new trends to shorten the time required. Despite efforts to restrict machine downtime [8], the majority of service impact on productivity is due to unexpected breakdowns, which are difficult to foresee and quantify in terms of time and effort. And, despite considerable work on the ground, it necessitates a lengthy process that reduces equipment availability. The same happens while working on MPRC, as MPRC deals with the assembly and dispatch of direction control valves when any need for maintenance arises the whole production system got stopped. To get the system back on track, the worker (users) needs to refer to the manuals, then identify the spot of dysfunction, and then work on the remedy to this dysfunction. This all led to wastage of time, and for this period MPRC will be under breakdown which eventually reduces the effectiveness of the firm. In this research work, to eliminate this ineffectiveness as early as possible, the augmented reality is applied to complete the maintenance activity, which will save time and cost (by reducing the breakdown period).

2.2 System Information

Multi-process robotic cell (MPRC) is a combination of five different stations, namely incoming conveyor, assembly station, testing station, hex nut assembly station and packaging station. With a six-axis KUKA robot, MPRC performs the required operations for the assembly of the direction control valves. Previously, all this work was done with the help of three different stations and the use of separate robots, but the implementation of MPRC reduces the previous work of 20-axis to 6-axis. KUKA robot has different tool changers, and with the use of different tools, the robot carries out the specified operation.

A conveyor carries inventory and pallets to the desired places from which the robot can pick up the inventory. Inventory and parts are labelled by RFID tags. After detection of RFID tags, the conveyor starts moving to get the inventory in reach of the robot.

The assembly station assembles the axisymmetric and prismatic parts. A robot picks up the parts from the conveyor and puts them on the assembly station where clamping and holding of parts are done with the help of pneumatic cylinders. Here at the assembly station vision inspection of parts is done by the robot and after detection of standard profile assembly work is carried out, otherwise, the part is placed in the rejection bin.

Testing station checks the leakages in the valve with help of the pressure buds by blowing compressed air through the ports of the valve body. If any air leakage is identified in checking then the valve gets rejected.

After testing the valve, it gets transferred to the hex nut assembly station. Here hex nuts are placed on the valve body and tightened with the help of a screwdriver by the robot. After tightening, the valve body is placed inside the carton for packaging.

At the packaging station, the robot changes tools and uses different tools for the packaging. The robot puts the parts inside the carton, and taping, printing and labelling are done at this station. After this station parts are ready for deployment.

2.3 Identified Critical Stations

In MPRC two stations are identified which are critical. The first one is the assembly station and the next is the testing station.

At the assembly station screw feeders are placed for the automatic feeding of screws to the robot. Sometimes its function gets disrupted because of some misalignment of parts and other reasons. Herein guidance of maintenance steps is given for the screw feeder which will help users to fix the problem and set the feeder back to normal functioning.

At the testing station, there are nylon buds present at the tip of air nozzles. These air nozzles blow air inside the valve body to check leakages. Sometimes these buds need to be replaced.

2.4 Maintenance Steps for Commonly Known Issues of Screw Feeder

Feeder pass plate error

1. Open the lid
2. Check the passing plate height
3. If the height is too low then it will not pass the screw and if it is too high screw passing will not be smooth
4. Loosen the passing plate attaching bolts and adjust it either up or down.

Feeder Rail and escaper plate clearance error

1. Open the lid
2. Check the clearance between rail and escaper plate

3. If the clearance is too high then the screw will fall inside the machine
4. Adjust the clearance by losing the rail fixing bolt with the help of hexagonal Wrench
5. Hold the rail groove
6. Adjust it by moving either backward or forward.

Adjusting the vibrations. If vibrations will be too much then the screw will fall down (jump down) from the rail.

1. Go to the back side of the machine
2. There are three knobs
3. Take the accompanying screwdriver
4. Adjust them according to the requirement of setup fast or slow.

Bud replacement steps

1. Hold the bud which is situated at the tip of the air nozzle
2. Pull it outside
3. Take a new bud
4. Replace the old bud.

3 Implementation of Augmented Reality for Maintenance

3.1 AR Framework

AR framework is shown in Fig. 2. It shows the flow of data from one place to the other. The identified maintenance activities and critical stations are named as use case identification. In this identified use case the AR experience is created. Figure 2 also represents the overall process flow of the AR experience. Each block in Fig. 2 represents a phase of implementation. In each phase different software are used to create required raw data for the AR implementation. In Fig. 2 at the bottom of each block, the used software is mentioned. Maintenance steps that are identified for the

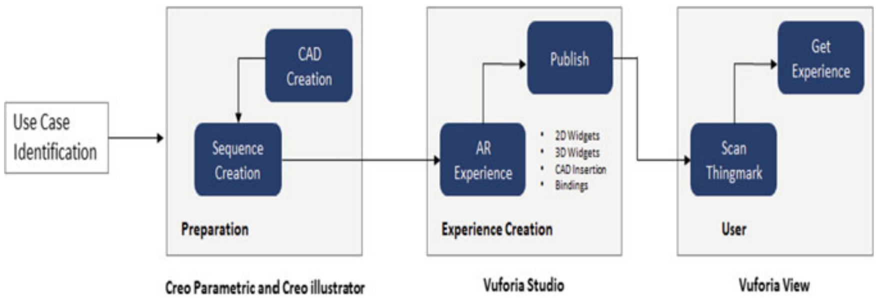

Fig. 2 Flow of information

use case are then converted into animation/sequence in the preparation phase. This prepared CAD and sequence are collaborated on Vuforia Studio to create a user interface and AR experience. This created AR experience is given to the user with the help of a QR code/thingmark. This is how information flows through each phase, and the user is given maintenance instructions.

3.2 Software and Hardware Used

PTC Creo Parametric is used for the creation of the computerized assembly of the MPRC. Here the actual CAD of MPRC is created for augmented reality experience.

PTC Creo Illustrate is used for the creation of 3D sequences which are required to guide the user on augmented reality experience.

Vuforia Studio is used for the creation of augmented reality experiences.

During the preparation phase the CAD is created with the help of Creo Parametric. This CAD is created with actual dimensions, which will then be superimposed on the physical system when viewed in AR experience. The CAD is created for screw feeder, assembly station and nylon buds. Figure 3 represents the actual CAD and part positioning of the automatic screw feeder. The maintenance activities are to be done on this screw feeder inside the assembly station. Sequences for maintenance activities are created on this CAD.

The user is guided through the maintenance process by sequences. These sequences are generated in Creo Illustrator, and when superimposed on the physical system inside the MPRC, they will be played as animations. These animations give step-by-step guidance to complete the maintenance process.

Different steps are created in Creo Illustrator, Fig. 4 represents some steps for maintenance of the screw feeder. The initial step which is required at the start of the maintenance is shown in Fig. 4a. Figure 4a shows the direction to remove the top lid

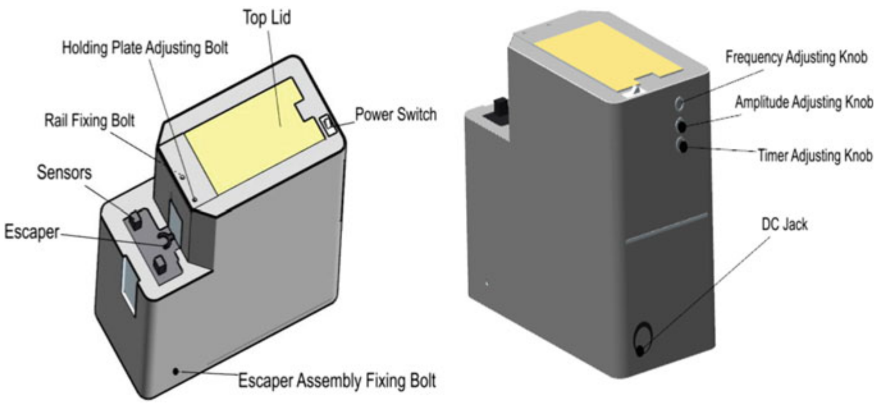

Fig. 3 Screw feeder parts

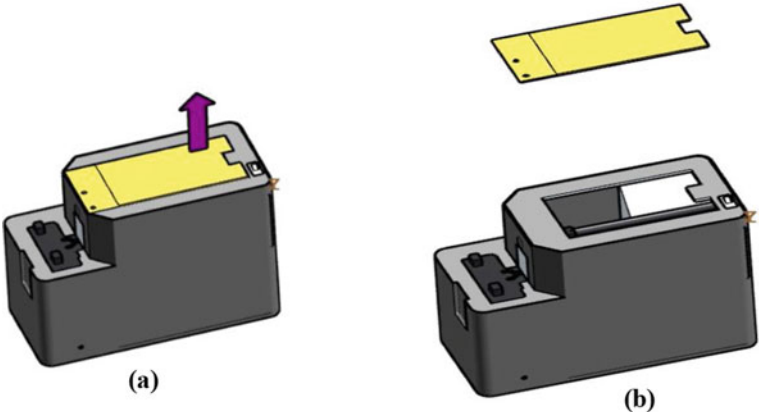

Fig. 4 Steps created in Creo Illustrator

to carry out further maintenance. Figure 4b shows the uplifting of the top lid to get the inner assembly view of the screw feeder.

These created CAD and sequences are then collaborated on one platform called Vuforia Studio, which starts the experience of creation phase. On Vuforia Studio the entire user interface of the mobile application is created and the sequences are bonded with the click of buttons. The various widgets present inside the Vuforia Studio are used to provide safety instructions. These widgets, user interface, CAD and sequences combined are called AR experience. Vuforia Studio provides one function where the experience can be previewed before the final publication. A preview of the AR experience is shown in Fig. 5. Figure 5a shows the home screen of the AR experience. When the thingmark is scanned Fig. 5a will appear on the mobile screen. When the MPRC button present on the home screen is pressed by the user Fig. 5b will appear. Figure 5b contains the steps that needed to be carried out to identify the location of the screw feeder inside MPRC.

The created AR experience is published and stored inside a QR code/thingmark, which needs to be scanned by the user to get inside the AR experience. The AR experience can be accessed either by head-mounted display [9, 10] or portable device [11]. The one hardware that is required to use this AR experience is the user's mobile. With help of mobile, the user will access the AR experience by scanning QR code/thingmark using the Vuforia view app.

4 Results and Implementation in Physical World

When the user scans the thingmark from the Vuforia view app, the user will get the views as depicted below. These views will help the user to setback the system in proper condition.

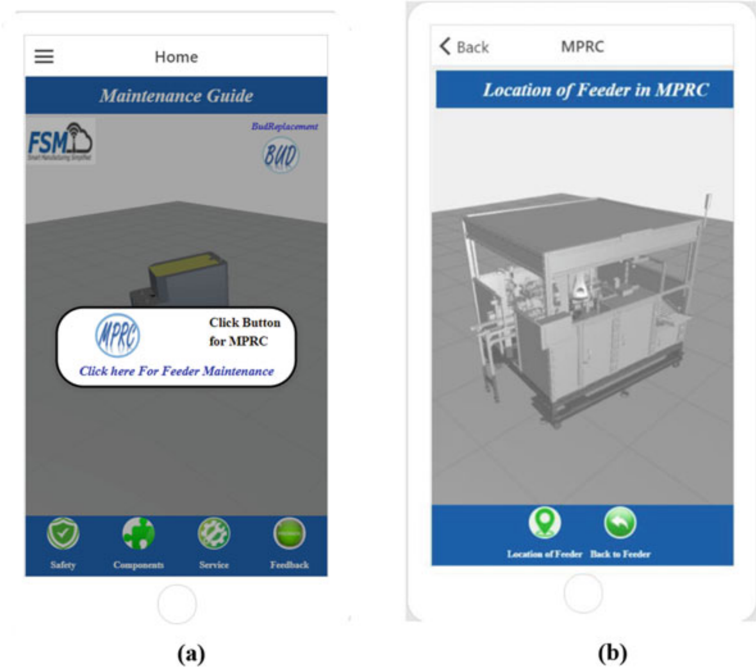

Fig. 5 Preview of augmented reality experience in Vuforia Studio

Figure 6a presents the initial view after scanning the thingmark. The initial screen contains different options linked with different screens. Figure 6b shows the bud replacement screen on which the user will be directed to carry out bud replacement. Figure 6e shows the transition when the user clicks the safety button present on the home screen such that safety instructions will show. Overall, Fig. 6 shows the various screens present in the AR experience. The users will give input by clicking the different buttons to navigate/switch from one screen to another. In this way the user will get detailed guidance to complete the maintenance process, which includes guidance from tool needed to safety steps.

5 Conclusion

The present paper describes the user interface, including augmented reality for manual instructions and step details, specifically for screw feeder and bud replacement which is one of the crucial activities in the assembly station of multi-process robotics cell. This augmented reality experience helps the user to get a clear understanding of removing the clearance error and adjusting the vibration of the screw

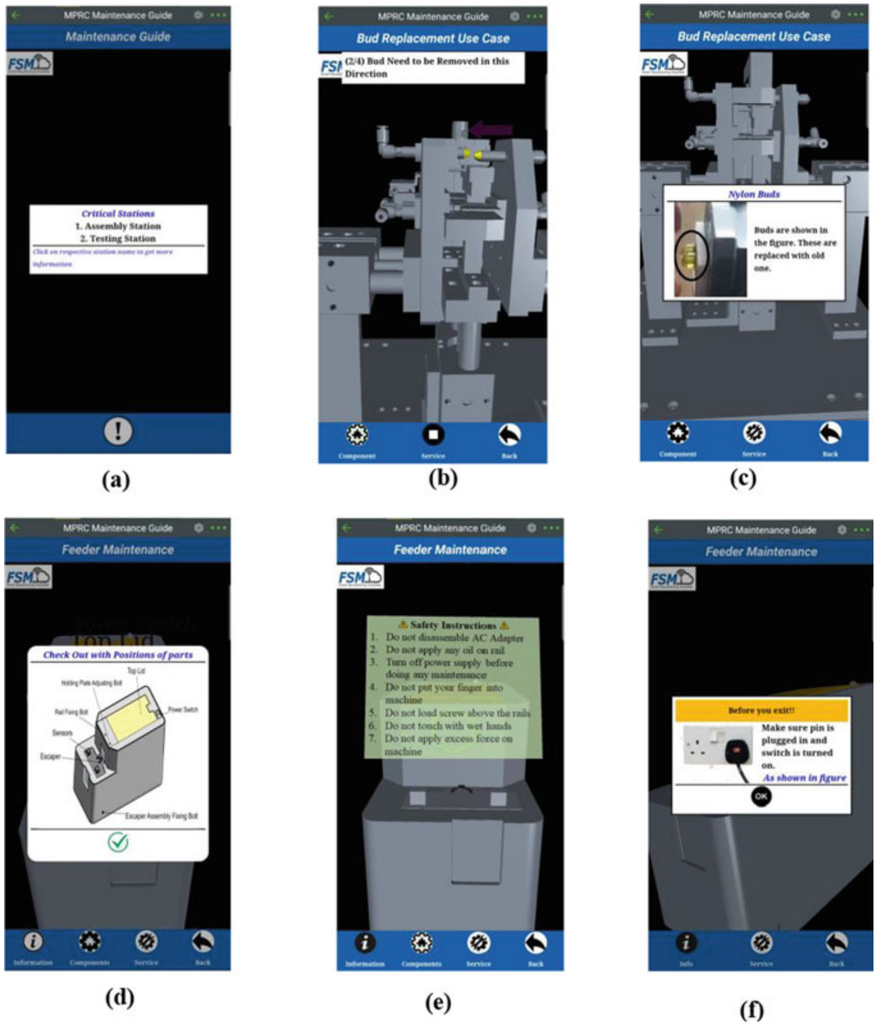

Fig. 6 Physical world superimposition

feeder. Before the implementation of AR, the time required to carry out maintenance activity by referring manuals is more, which creates a breakdown in various segments that led to an increment in cost. But the implementation of AR reduces the time required and eliminated inefficiency. Also, this offered AR instruction at MPRC that assists users in obtaining a detailed methodology for performing maintenance. This experience not only assists the user in following all of the directions but also in visualizing the procedure to finish maintenance activity effectively.

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Augmented Reality Implementation for Fault Diagnosis on Robotic Welding Cell

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1 Introduction

Industry 4.0 is the fourth stage of the industrial revolution, which plays a key role in the development of the third industrial revolution. It is a digital transformation process from automated factories to intelligent factories. Industry 4.0 was referred to as an integration of information and communication technology in industrial manufacturing when it was first started. Industry 4.0 is the ongoing automation of traditional manufacturing processes, enabling industries to share data and collaborate with various elements involved in the supply chain. The various technology elements associated are smart machines, IIoT, augmented reality, machine vision, smart sensors, big data, robotics, digital twin, additive manufacturing, and predictive maintenance along with cyber-physical systems which play a key role in digitally connected factories. Smart manufacturing is concerned with reducing all the time elements such as introduction, growth, maturity, and decline stages involved in a product life cycle.

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Industrial robots are one of the applications of Industry 4.0 which play a key role in this digital transformation of factories whose positioning and operations must be planned appropriately [1].

The digital technology used in this project is augmented reality (AR) which is used to train users of industries adopting smart manufacturing. AR has a large market value if implemented in many industries and organizations. Augmented reality converges the digital and physical world giving a better edge to a range of applications. The physical world is three-dimensional and the data of this would be embedded on 2D screens and pages, and this difference between the physical and digital world prevents human capabilities for better usage of data. This disadvantage can be bridged by AR. AR changes the user's perception of the real world or uses certain widgets like images, labels, and tags to overlay virtual data on the physical world. AR creates business value by becoming part of a product through devices like AR display heads-up, smart glasses, wearables, and also its experience can be viewed on mobile phones. AR reduces the cognitive load on humans by digital information overlay. The key capabilities of AR are visualize, instruct and guidance, and interaction with users. Visualize refers to the visualization of internal features of a real complex system, instruct and guide describe step-by-step guidance on tasks like product design and assembly operations, and interaction feature enables the activation of a virtual user interface by replacing physical controls like buttons by using smart glasses and headsets.

The Internet of Things (IoT) also plays a key role in providing real-time data for fault diagnosis and other applications. This has embarked new IoT-powered augmented reality applications in many ways like system replacement, training, etc. Fault diagnosis is one of the major applications of the combined technology of AR and IoT [2]. Robotic welding is one of the use cases of fault diagnosis. The welding mechanism plays a key role in the development of hardware systems. With the continuous development process in the industries, manual welding has been eliminated since it is more difficult and also impacts the health of the system. This may lead to a delay in product production [3]. Apart from this, other researchers have identified various applications of AR in maintenance. Diagnosis, training [4], performance measurement [5] are some of the studies which are currently ongoing in the industries.

This paper gives a detailed explanation of how critical systems of robotic welding cells are analyzed, after which the faults are monitored from tower light through real-time data, and users are instructed to take corrective actions to diagnose the fault identified in safety systems by AR experience created through Vuforia Studio. Continuous monitoring of the system is a must to identify faults and inform the user to correct them.

2 Proposed System

Industrial robotic welding cell, which is a flexible manufacturing cell like any other machine, requires frequent maintenance. Fault diagnosis is the primary step to effective maintenance which identifies faults, and correction is done as a remedy. Different software is involved in the overall process. Thingworx IoT platform has its key role in collecting the monitored data of the safety systems fault and Vuforia Studio helps in creating and publishing an AR experience. AR experience can be created through the following tracking methods in Vuforia Studio. They are as follows:

- Marker-based AR requires a marker to activate an augmentation.
- Markerless AR offers the control to the user to choose where they would like to place the content such as based on location.
- Projection-based AR is a video projection technique that expands and strengthens video data by launching images on 3D spaces.
- Superimposition AR uses object recognition where the augmented image partially or fully replaces the original image [6].

In this work, a thingmark-based target is used. Figure 1 displays the AR development workflow which describes the hardware and software components involved in the development process of augmented reality applications for fault diagnosis.

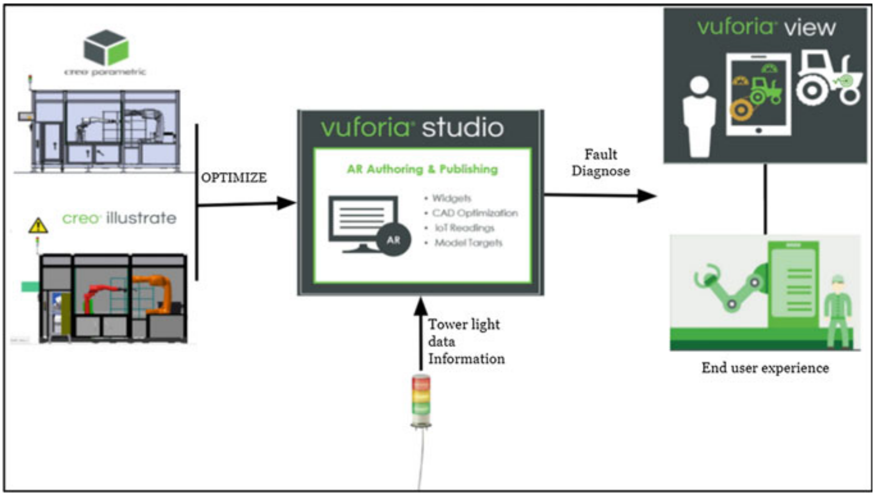


Fig. 1 Block diagram of process flow [7]

2.1 Hardware and Software Components

Robotic Welding Cell (RWC)

The welding cell used in our application performs MIG welding and additive manufacturing. It is a flexible manufacturing cell—meaning it has its inventory, material handling system, and various parts in random order. The order can be placed using an app or manually using an HMI. There are two robots for performing the welding operations. The important components involved in the robotic welding cell are listed as follows.

Two robots

There are two robots involved in the process. The first one is the welding robot, which is a 6 degree of freedom articulated robot with the model—KUKA KR8 R1420 arc HW used to weld the workpiece, and a welding torch is mounted on this robot. The second is a material handling robot that moves the pallet fixture inside the welding cell with the model—KR30 R200 and is used to hold the workpiece.

Fronius Mig Welding Power Source

It provides the power for welding through a welding torch present on a welding robot and supplies current to it. The model is Fronius TPSI 400 CMT [8].

Torch Cleaning Mechanism

After the welding process, the welding torch attached to the welding robot has to be cleaned. The torch is immersed into the torch cleaning solution to remove the burr after the welding process. The model is Reamer V Easy.

Storage Rack

It is used to store the workpiece and welded part.

Human–Machine Interface

It is the interface between the controller and the user where most of the controls are run through it. The model is EXOR EX715 [9].

Safety Systems and Sensors

To detect errors or faults inside the RWC, various safety systems are installed, which must work efficiently to protect the workspace and the people working in the area. Safety components are as explained below.

Light curtain

Light curtains are present in this station for safety. If there is a breach in the light curtain, the machine will stop and it will move to a safe position after the light curtain is reset. This is an advanced method of securing the area around hazardous machines. The transmitter unit consists of light-emitting diodes (LEDs) that emit invisible infrared light pulses when energized by the light curtain's timing and logic circuitry [10].

Emergency stops

If the emergency stop is pressed, the machine will be reset and stopped. If any kind of mal-performance in the machine is observed, then this switch must be pushed which disables the power supply of the welding cell causing the system to stop immediately. This button is connected to the control circuit for its use in an emergency crisis.

Safety interlock

The door is integrated with safety solenoid interlocks. When the door is open for maintenance or an operator is working inside the cell, the programming will be in an idle state. Once the door is locked, the system resumes.

Tower Light

The tower light indicates the safe working of safety systems which have three lights in them. It is used to alert the user in case of any malfunction in the system. It consists of red, amber, and green colors. It is an L-bracket aluminum tube mounting.

Sensors (Data on IO-Link Master)

IO-Link is an industrial communications networking standard involved in the connection of sensors and actuators to a type of field bus or ethernet [11]. IO-Link master collects the data from these sensors and sends them to plc to control the output. It also sends data regarding the health state of the sensor and monitored data.

Figure 2 shows the control architecture of RWC working which represents the controllers and related electronics involved along with cloud systems in the process.

Creo Parametric and Creo Illustrate

Parametric is a software product of Creo used for 3D modeling. It is design software for creating parts and assemblies. Through this CAD models can be integrated into Vuforia Studio for AR implementation. Illustrate is an animation-creating software tool for 3D models that helps to apply animation sequences to guide a user by connecting to the AR experience [12].

Thingworx and Vuforia Studio

Thingworx [13] is a developer platform to create IoT-powered augmented reality to collect real-time data and integrate it into Vuforia Studio which is a web-based tool having CSS stylers, 2D and 3D widgets creation environment where AR experience is created and published. This can be viewed through Vuforia view app [14].

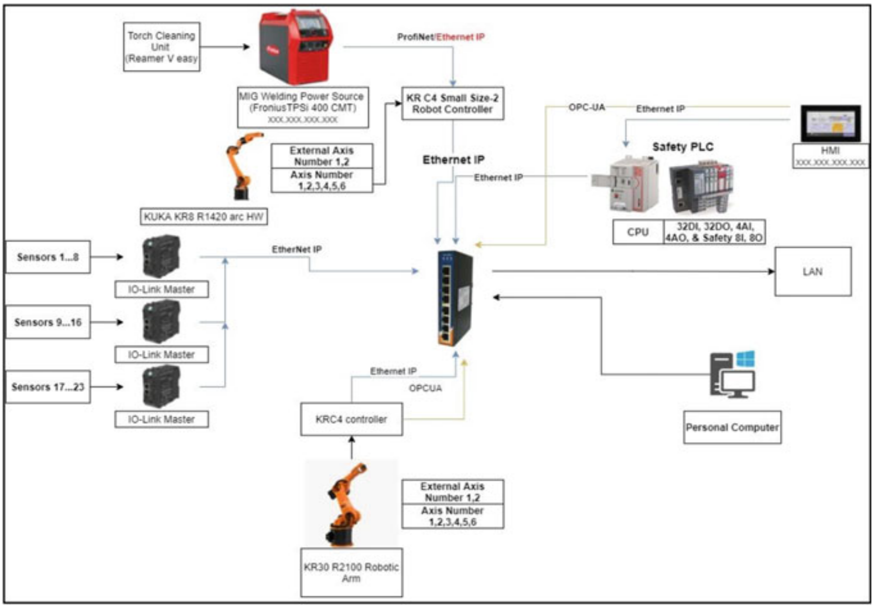


Fig. 2 RWC control architecture V2

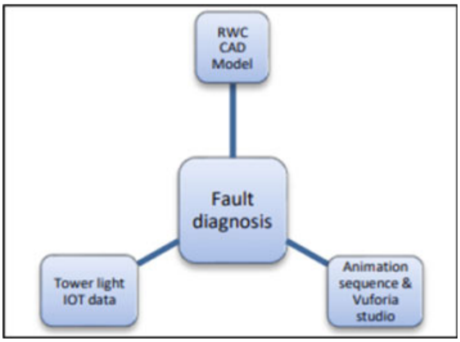
2.2 *Methodology*

Various steps are involved in implementing AR on RWC for performing fault diagnosis. Figure 2 describes the flowchart of the methodology overflow. The steps are as discussed below (Fig. 3).

CAD Model design

The basic parts involved in robotic welding cells are designed in Creo Parametric software considering the workstations which involve load/unload area, inventory

Fig. 3 Implementation plan



storage area, inspection, and operations area. Using the same software, the components designed are then assembled to create a final assembly of the RWC model. Later, the safety systems are designed separately as per the standard model numbers considering the safety design parameters like threshold distance, vertical height placement, user-centric, etc. These are then assembled onto the final RWC model at the specific locations. Tower light is placed on top of the cell for easy monitoring, HMI and emergency pushbuttons are placed at the front side of RWC for user-friendly handling, and a safety interlock is located on the door for a more secure entry into the station along with speedy progress.

Creating Animation Sequences

The 3D CAD model created in Creo Parametric is imported to Creo Illustrate to create animation sequences for the fault diagnostic operations. The animation sequences have been created for all the safety systems separately for the user to receive guidance to rectify the errors. The exploded view and motion effects along with color characteristics have been implemented in the model to provide detailed user guidance on fault diagnosis. This platform has features like camera and capture which play key roles in sequence and animation creation. RWC model sequences are then imported as a 'pvz' file to Vuforia Studio for creating an AR experience. The figures of the 3D model and its illustration created are displayed below (Fig. 4).

Importing real-time IoT data

The Thingworx platform is used to import real-time data, for fault diagnosis operations. In this work, tower light indicates whether a safety system is working normally or has a particular error that leads to safety system breakdown. This tower light data will be monitored to indicate faults of the safety system and diagnose them by using

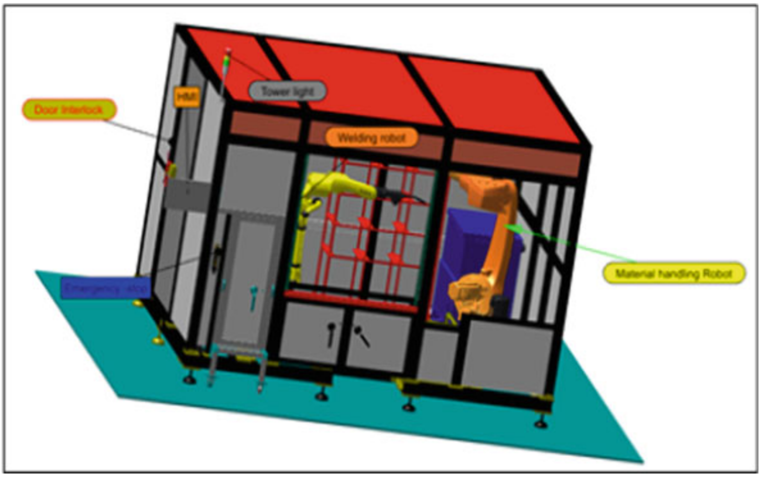


Fig. 4 RWC CAD model illustration

the reset button. Safety systems are used when there is a particular error or fault occurring inside the robotic welding cell which has to be monitored first. For instance, if any part of the system, for example, the robotic arm has stopped working, this fault must be monitored to indicate the user to use safety systems to diagnose the error. Thingworx data is integrated with Vuforia Studio for further implementation of AR. In the Thingworx platform various entities, subscriptions, and events are created.

Creating and Publishing AR experience

Vuforia Studio is used to create AR experiences that can be viewed through the Vuforia view application on mobile. There are two modes—first is the 3D canvas where a target is set using thingmark with a marker width of 0.02 cm and the 3D sequenced model is imported on it and adjusted to a scale of 0.3. After this operation, the 2D canvas is worked where various 2D widgets like buttons, labels, card data, popup, etc. are imported to create an effective AR experience for fault diagnosis. The 2D widgets are bound to various services and events are triggered. Through external data, the IoT data tag can be imported and integrated into Thingworx. CSS styling code is implemented for a better user experience. For a better AR experience, UI design was first worked in proto software to create mockup screens and then applied in Vuforia Studio. Multiple screens are created to take the user through different options. It is then published and experienced through a QR code and Thingmark scanner (Fig. 5).

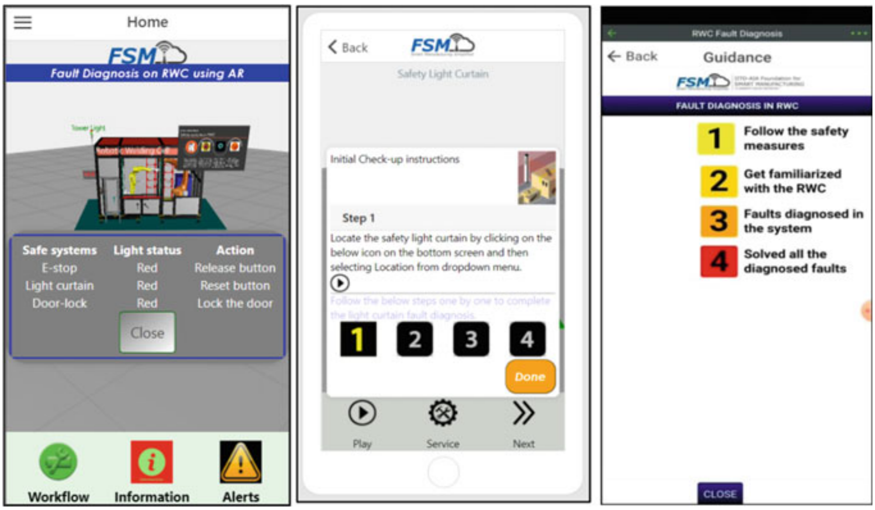


Fig. 5 Mockups and 2D widgets design for AR implementation

3 Results

The results of an effective AR experience for fault diagnosis are viewed in the form of a 3D visual display in the physical world. In the fault diagnosis performance, tower light display indication plays a key role in this proposed project. When the tower light indicates red, it infers that there is a particular error or human intervention in the safety system, upon which reset button is pressed in Vuforia Studio AR experience created to bring the safety system back to the error-free device and smooth working. In case the error continues, further user guide instructions and sequences are described. For example, in the case of a light curtain, when the transmitter or receiver is rotated by 10 degrees, the system will start working smoothly and then the tower light indicates green color. In case the safety system is currently in use, then the tower light indicates yellow color. All the processes of tower light in the fault diagnosis as described are integrated into the actual AR experience. The functional working results of AR experience are represented in physical view as shown in Fig. 6. Vuforia view app is used to view the AR experience in physical view by scanning the thingmark generated. Table 1 describes the comparison between the conventional approach and the AR experience used in fault diagnosis application [15].

4 Conclusion

This paper proposes an integrated approach to implement AR on industrial robots for fault diagnosis using real-time IoT data which can be experienced via mobile phones. AR and IoT use case implementation in any application impacts huge benefits to the

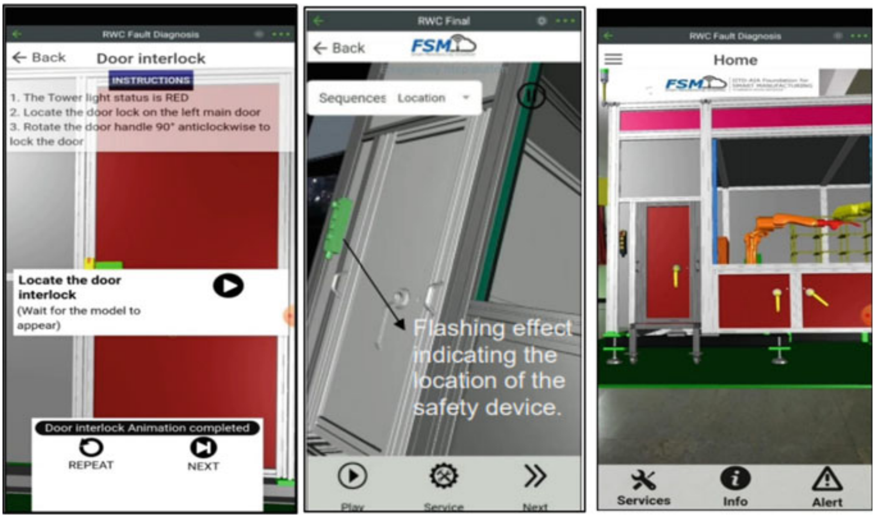


Fig. 6 AR experience in physical (Vuforia) view application

Table 1 Comparison of conventional approach and AR approach

Features	Conventional approach	AR approach
Complexity	Requires a fair amount of data	Requires a physical model
Fault detection	Latency period of smart systems is increased	Reduces decision and action latency and real-time data
Training	Physical presence, risk involved	Remote training, user interface with a virtual experience

user as well as industries. Fault diagnosis, machine monitoring, and maintenance training are some of the use cases where these key technologies along with data spread play a vital role. Remote maintenance is another key advantage of implementing AR in industries. The fault identification at an early stage reduces severe breakdown and production losses, which is most needed in the current generation of industries. In this work, fault diagnosis on one application use case of industrial robots is performed. It can also be performed on various applications of industrial robots such as finding looseness in a robotic mechanism, predicting system response and tuning the control system, and controlling the material inflow and welding torch mechanism, etc. Predicting the life of various systems using AR and IoT data collected from sensors is one of the key applications implemented in Industry 4.0. Results suggest that safety systems can be analyzed easily using IoT data as indicated on the tower light. Future developments would be focused on implementing AR experience for various other applications on wearables and heads-up displays.

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Impact of Additive Manufacturing in SMEs

Idil Tartici, Zekai Murat Kilic, and Paulo Jorge Da Silva Bartolo

1 Introduction

Small and medium-sized enterprises (SMEs) can be defined as the companies with less than 250 employees and an annual turnover of less than 50 million € or an annual balance sheet of not more than 43 million € [1]. The impact of SMEs in the global economy is crucial because 90% of companies comprise SMEs, and 2 in 3 jobs are created by SMEs [1]. Nowadays, SMEs are at risk caused by the late adoption of digital transformation despite all their potentials in the economy. The core reasons for these risks are increased competitiveness, the necessity of the fast response of the market demands, and larger companies increasing their ability to produce flexible, low-cost, and small-batch manufacturing by implementing Industry 4.0 (I4.0) technologies [2, 3].

Additive manufacturing (AM), which is one of the design rules and the trending technology of I4.0, helps to manufacture SMEs to reach these goals in a single digital transformation step [4]. The basic definition of AM is producing products by using accumulating materials as layers according to the computer model [4]. The materials used in the AM process can vary from plastics to metals, and this provides flexibility to produce a wide range of products [4]. Contrary to traditional manufacturing methods, it reduces waste and design limitations besides decreasing the manufacturing time.

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Despite the benefits of AM process mentioned above to the manufacturing SME, there are not many studies presenting why SMEs are not willing to replace traditional manufacturing systems with advanced manufacturing systems, and what challenges they experience during the adoption of advanced manufacturing systems [5]. In this paper, we aim to address this gap with the following objectives: (1) Listing fundamental challenges encountered by the SMEs during digital transformation; (2) determining the main challenges faced by SMEs that used or plan to use AM and defining the potential market; (3) discussing the impact of AM in SMEs.

The article is divided into three parts: the introduction part gives basic information about SMEs, I4.0 technologies, and challenges faced by SMEs during digitalization and at the same time summarizes the aims of the article. The research perspective and discussion part of the article focuses on the challenges in the implementation of AM for SMEs, besides potential niche sectors. The conclusion part summarizes the research and results.

2 Literature Review

2.1 Industry 4.0 and Small and Medium-Sized Enterprises (SMEs)

The idea of the fourth industrial revolution (I4.0) is applying digital technologies to gather meaningful data and using these data to improve the performance of the systems [6–10]. Because of the high cost of new technologies, I4.0 technologies are applied by large companies, which have sufficient financial resources. The aim was to use them to reduce their waste by controlling machine usage and production parameters and increasing productivity and run time by decreasing the unpredictive maintenance. On the other hand, SMEs, which have restricted financial resources, have difficulties adapting their traditional manufacturing systems to I4.0 technologies. When the role of SMEs in the global economy is considered, the reasons behind the late adoption should be researched, analysed, and alternative solutions should be recommended to SMEs. After the term "Industry 4.0" was coined in 2011, research outputs that include both of the terms "Industry 4.0" and "SMEs" began appearing in 2013 and kept increasing towards 2016 [6, 11]. According to the "Scopus" database results, Fig. 1 shows the increasing trend of the number of annual publications during 2013–2020.

Although originally appeared in Germany, the term Industry 4.0 was modified and adopted by many countries under different names such as "Made Smarter" in the UK, "Made-in-China 2025" in China, and "Smart Manufacturing" in the USA [12]. All these digital transformation strategies prove the importance of I4.0 in the global economy. The main pillars of I4.0 are summarized in article [13].

In the literature, research related to I4.0 and SMEs starts with the roadmaps and maturity models to analyse the current information technology (IT), finance, and

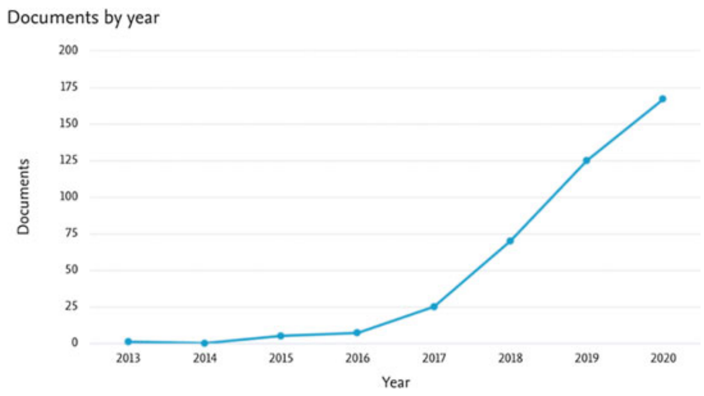

Fig. 1 The number of annual publications in the fields of both I4.0 and SMEs [11]

technological situations of SMEs. To exemplify, Ghobakhloo created a strategic roadmap to help SMEs as guidance firstly to define digital technologies related to the processes, secondly, control the progression in these digital technologies, and finally, time management during the digital transformation [4]. Moreover, Mittal et al. critically reviewed the maturity models and concluded that current maturity models and frameworks do not show the real situation faced by SMEs [14].

There is various research in the literature regarding the challenges faced by SMEs during digital transformation. Some researchers have had surveys with SMEs to better understand why SMEs cannot adopt their systems to I4.0 technologies, while others directly collaborated with them to analyse the current challenges in digital transformation. Masood and Sonntag researched the effects of company size (small, medium, or large), I4.0 perspective, and complexity of the manufacturing (project-based, batch, or mass) on the digital transformation of SMEs [5]. The participants of the research consist of more than 270 UK SMEs and results show that the size and I4.0 perspective of the companies have a positive impact on the adoption of the I4.0 technologies [5]. However, process complexity is one of the main barriers to adopting digital transformation because it needs more expert knowledge and high-tech devices [6].

In 2019, Prause developed a "technology adoption model" by collaborating with 38 Japanese SMEs [15]. The research pointed out that the position of the company in the industry has a critical role in the adoption of digital technologies by SMEs and it provides short-term benefits [15]. Moreover, the support from the top management of the companies has a positive impact on the adoption process in the long term [15]. Another important parameter influencing the success of SMEs is the financial sources [16–18]. This means that financial barriers of SMEs block replacing traditional manufacturing systems with advanced ones or purchasing new technology devices to modify old manufacturing lines. In addition to the financial source, Ingaldi and Ulewick have mentioned that employee cooperation, restricted product range, and fluctuations in demand and economy in the surroundings of SMEs influence the digital adoption process [17, 19, 20]. Furthermore, organizational parameters affect transformation such as the level of the hierarchy and the decision-making progress [16–18, 21, 22]. Additionally, cooperation between academia and industry is needed by SMEs to increase awareness, understanding, and implementation of the multi-dimensional field of I4.0 [14]. Lastly, the connection of the devices with the Internet and managing manufacturing using IoT technology made SMEs that lack expert knowledge about cyber-security vulnerable to cyber-attacks so security concern is another barrier in front of the SMEs [23].

Cotrino et al. mentioned three gaps in the literature. The first gap is the lack of real-life low-cost implementations of I4.0 technologies for SMEs, the second is that existing digital transformation roadmaps do not match the characteristics of SMEs, and the last is that SMEs do not have enough knowledge to select and implement digital technologies [24]. Finally, the latest studies in this field have begun to focus on cost-effective digital solutions and their implementations in SMEs to fill the gaps [24].

2.2 Additive Manufacturing

Additive manufacturing technology emerged in the 1980s in Japan, and various methods were discovered by the title of 3D printing [25]. The selective laser sintering (SLS) method was invented after 3 years of the first 3D printing machine and was presented to the market for commercial use in 1990. Bio-printers were generated endmost of 2000 and have been used to fabricate a kidney [25]. The ability of AM machines to print various types of materials (e.g. plastics, metals, and biomaterials) and produce complex designs has given unique manufacturing opportunities for the manufacturers [26, 27]. According to the American Society for Testing and Materials (ASTM), the AM process is grouped under seven methods [28], and details of these methods can be found in [21].

When compared to the traditional manufacturing systems, AM enables flexible design and material opportunities, reduces manufacturing time and waste, creates opportunities to produce low-batch customized goods while minimizing the number of production steps [26, 29]. The aforementioned benefits draw the attention of the manufacturers to the AM [17]. This advanced manufacturing technology is currently applied in aerospace, machinery, electronics equipment production, and medical goods, and the application areas keep expanding with the new technologies.

3 Research Perspective and Discussion

Additive manufacturing became popular among the manufacturer SMEs due to advantages such as part producing with a multi-material and creating the complex parts in a single step [2, 17]. Recent research shows that the AM process boosts the income, product price, and competitiveness of the SMEs besides decreasing the time to market and waste [17, 18]. SMEs are willing to additive manufacturing systems despite the struggles of their implementation in their business. To accelerate the adaptation of AM in SMEs and to find low-cost digital solutions, the difficulties encountered in the adoption process should be analysed. For this reason, the literature has been searched and findings have been explained under three titles.

Machine, Technology, and Material—Producing high-range and personalized products is a key specification of SMEs. The AM process supports them expanding their product portfolio, but the size restriction of AM machines limits the product size [2]. The maturity level of the AM technology is another barrier in front of SMEs. This means that the AM technology needs to improve in both machine specifications and material options. Another technology limitation is related to the software [2]. SMEs can hardly financially afford the software systems. Cyber-security and file exchange issues are additional challenges with cyber-attack risks on manufacturers or customers and variation of quality among design documents [22]. The material-related challenges are more about the material restrictions used in AM machines and the necessity of the new supply chain for SMEs [18, 20].

Process, Fabricated Parts, and Standards—The first and foremost barrier related to the process is lack of the skilled designers to estimate production methods and post-processing [2]. This lack of knowledge among the employees causes part quality issues as well [2, 17, 18]. Besides, long fabricating time and the necessity of post-processing are other challenges for SMEs [30]. The quality of the fabricated parts such as the level of porosity and stability is another barrier [30]. Moreover, lack of standards both between different machines and the processes causes late adoption of the AM process among manufacturing SMEs [2, 30, 31]. Last but one of the important barriers is the lack of knowledge about the optimization of the AM process; the optimization process needs more expert knowledge about both machines and processes [2, 26].

Finance, Organization, and Market—The high initial investment cost of AM machines and the cost of post-processing are the main financial barriers to the adoption process [2, 7, 21]. In addition, SMEs do not want to take the risk of adopting new production systems due to the limited financial resources [2]. The adoption of a new manufacturing system affects each department in the company, and a company-specific roadmap is needed to adopt this new system, e.g. the marketing department should find new potential markets to sell the products or the purchasing department needs to find new suppliers [27]. Moreover, the lack of potential market knowledge and a clear strategy to adopt AM in SMEs was pointed out by researchers [2, 3]. The other organizational barrier is the poor connection between the customer and manufacturer for part design and production improvement [2]. A successful connection creates benefits for both sides to optimize product design and material selection. In addition, the company staff should be trained about both the adoption process and the new manufacturing method to speed up the adoption process [2, 18, 21].

The potential market research was done by Rauch et al. to identify future industrial fields of implementation of AM in the SMEs [3]. They listed the top promising manufacturing industries [3]. The medical industry took first place as a potential industry for SMEs to apply AM. Examples of this sector are manufacturing kits for surgical operations, and the production of implants and biomaterials for treatments [29, 32, 33]. In the application area of accessories, fabrication of real and imitation jewellery is another potential market for SMEs. Concretely, the research on the potential markets has no company size restrictions. Therefore, in the future, SMEs and large companies will compete in the AM field, and SMEs should adapt to AM as soon as possible.

4 Conclusion

Literature review shows that the SMEs faced nearly the same adoption challenges related to I4.0 and AM. Table 1 summarizes all these challenges regarding digital transformation and the AM process. To briefly mention core barriers to digital transformation, the first barrier is lack of financial resources cause obstruct development decisions and new investments. Another barrier is the lack of skilled staff to learn, develop, optimize, and implement new technologies; each level of the organization should be updated to adopt a new manufacturing system from procurement to sales and marketing. The support from the top management, IT maturity of the company, and cyber-security concerns have a critical role in the adoption process. On the other hand, the AM technology is developing rapidly, and its benefits cannot be fully understood by SMEs. While the barriers to the AM process for SMEs may seem similar to the digital transformation process, there are some differences regarding the AM process itself. Size restrictions, lack of knowledge related to the software, standards, and design and development of the products are barriers related to the AM process. On the other hand, material restrictions and the need for a new supply chain cause late adoption of AM processes by SMEs. The optimization of the AM process is another challenge for SMEs because it needs expert knowledge and a deep understanding of the process parameters and their effect on produced parts. Furthermore, the high initial cost of AM machines and the risk of new production system transition made it difficult for SMEs to decide to implement AM. To overcome all these issues, manufacturing SMEs can be trained and financially supported by governments. Moreover, the collaboration between universities, research centres, and manufacturing SMEs helps them to understand, adopt, and implement the AM technology. Potential markets should be investigated in detail because short-term profits play a critical role in technology adoption for SMEs.

Table 1 Challenges during the adoption of AM and DT for SMEs

	Maturity level of IT
Digital transformation challenges for SMEs	Technology
	Cyber-security
	Complexity of the manufacturing
	Narrow product range
	Finance
	Participation of employees
	I4.0 perspective of the company
	Size of the company
	Decision-making hierarchy
	Fluctuation in demand
	Top management support
	Position of the company in industry
Additive manufacturing challenges for SMEs	Size restriction of AM machines
	Maturity level of AM technology
	Software (cost and skilled staff)
	Cyber-security
	Material restrictions and necessity of new supply chain for SMEs
	Lack of the skilled designers
	Lack of knowledge about AM
	Long fabricating time and necessity of post-processing
	Quality of the fabricated parts
	Lack of standards both between different machines and the processes
	Lack of knowledge about the optimization of AM process
	High initial investment cost of AM machines and the cost of post-processing
	Risk of adopting new production systems
	Lack of company-specific roadmap to adopt AM
	Lack of potential market knowledge and a clear strategy to adopt AM in SMEs
	Poor connection between the customer and manufacturer for product development
	Training of staff

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Industry 4.0

Application of Graph Theory Approach for Analyzing IoT Challenges in Maintenance Parameters Monitoring

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1 Introduction

With the advancement in technology, the fourth industrial revolution, also known as Industry 4.0 (I4.0), introduced various disruptive technologies that completely modified the manufacturing process and enabled machines' real-time monitoring [1, 2]. The technologies in the fourth industrial revolution accelerated manufacturing activities with improved functionalities. One such technology is Internet of Things (IoT)/ Industrial IoT (IIoT), which is gaining more attention from several industries due to its real-time monitoring capability, flexibility, scalability, connectivity, and cost and time savings [1]. IoT is one of the most significant developing technology of I4.0 coined by Kevin Ashton in 1999 that intends to modify the existing machines into programmable network devices with the help of sensor technologies, ubiquitous connectivity, and radio frequency identification devices [3]. Despite having all the advantages of IoT system, several challenges exist in its adoption in maintenance monitoring that needs to be explored. Therefore, the present study aims to identify the potential challenges of IoT in maintenance monitoring through a comprehensive literature review and analyze its influence in maintenance parameters monitoring using Graph Theory (GT) approach. Graph Theory methodology provides the interrelationship amongst challenges and helps to identify the most significant challenges [4]. The novelty of the study lies in contributing to the analysis of IoT challenges in maintenance monitoring using structural modelling approach, i.e., Graph theory. The objective of the research includes identifying IoT challenges with respect to maintenance parameters monitoring and analyzing its influence by establishing the interrelationship amongst potential challenges using Graph theoretical approach. The flow of the paper is organized as: The literature review of the study and research gaps are shown in Sect. 2. Section 3 provides details on Methodology. A case study has

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been presented in Sect. 4. Results and discussions are presented in Sect. 5. Practical and Managerial implications are shown in Sect. 6. Finally, Conclusions are presented in Sect. 7.

2 Literature Review

The literature review has been carried out related to the challenges of IoT adoption in addressing the maintenance aspect of manufacturing industries.

Compare et al. [1] presented a comprehensive view of the present predictive maintenance issues intending to deliver a deeper understanding of strengths and limitations, opportunities, and challenges with respect to industrial maintenance aspects. Roy et al. [5] introduced technologies and foundations needed to deliver maintenance services. The authors discussed the significance of Industry 4.0 and recognized the role of cyber security, IoT, and standards regarding continuous maintenance in the future. Further, Tedeschi et al. [6] introduced the universal strategy for secure IoT design with respect to maintenance of machine tools. Kumar and Iyer [7] explored the challenges and benefits of an industrial IoT in the manufacturing and engineering industries. Chen et al. [8] discussed the challenges in parts inventory management of maintenance, repair, and operations. They presented the significance of emerging Industry 4.0 technologies, namely, IoT, additive manufacturing, big data analytics, etc., in addressing it. Chowdhury and Raut [3] presented an outline of industrial IoT architecture and highlighted its significant application areas, challenges, and benefits to connectivity and scalability functionalities. Christou et al. [9] presented the design, architecture, and practical adoption of end-to-end industrial IoT systems to overcome the challenges with respect to predictive maintenance. Alfandi et al. [10] investigated the significance of blockchain technology in handling security and privacy issues in the IoT ecosystem. The findings of the study provided a deeper understanding of the integration of IoT and blockchain technology to resolve privacy and security challenges. Ingemarsdotter et al. [11] provided an understanding of 19 challenges pertaining to condition-based monitoring adoption and delivered 16 solutions from those who had implemented and derived a framework depicting the analysis of solutions and challenges in each case. Gbadamosi et al. [11] proposed an IoT implementation strategy in the maintenance of the rail industry based in the United Kingdom (UK) and discussed the challenges associated with rail asset management and recognized core dimensions for IoT adoption in rail asset maintenance. Further, Sekar et al. [12] reviewed difficulties in maintaining the accuracy and reliability of IoT systems prediction of remaining useful life of component. In the present study, 24 potential challenges of IoT with respect to maintenance monitoring from four dimensions had been identified through literature review and expert opinion. Table 1 shows the challenges of IoT with regard to maintenance monitoring.

Table 1 IoT challenges with regard to maintenance parameters monitoring

Dimension	IoT challenges	Description	Code	References
Connectivity (C1)	Integrating information technology (IT) and operational technology (OT)	Integration of IT and OT to smoothen monitoring and processing of industrial operations	C_1^1	[7]
	Lack of connectivity between different components and machine management	Connectivity between different components and machine management helps in establishing IoT in maintenance monitoring	C_2^1	[7]
	Integration with legacy technology	Legacy technology refers to the existing system. Its integration with IoT aids in maintenance monitoring	C_3^1	[3]
	Connectivity concerns and faulty sensors can lead to incomplete data recordings	Connectivity issues leading to collection of incomplete data	C_4^1	[14]
	Inability to combine multiple maintenance modalities based on advanced analytics	Incompetence in integrating the multiple maintenance modalities using advanced analytics	C_5^1	[9]
	Limited communication between personnel and R&D about maintenance requirements	Less communication amongst personnel and R&D influences the maintenance activities	C_6^1	[11]
Data management (C2)	Data integration	Date integration refers to the maintenance data collection in IoT	C_1^2	[3]
	Inflexible maintenance data collection	Lack of systems for flexible maintenance data collection	C_2^2	[1, 11]
	Lack of high quality of maintenance metadata	High quality of maintenance metadata provides accurate maintenance predictions	C_3^2	[11]
	Available data not fit for the purpose of IoT based maintenance	Existing data not suitable for IoT based maintenance	C_4^2	[11]

(continued)

Table 1 (continued)

Dimension	IoT challenges	Description	Code	References
	Data fragmentation and lack of interoperability across different datasets	Interoperability issues in existing machine systems leads to poor maintenance	C_5^2	[9]
	Lack of awareness about maintenance monitoring	Lack of awareness about maintenance monitoring influences adoption of IoT in maintenance	C_6^2	[11]
	Lack of tools to support developers with data access and processing	Tools unavailability to facilitate developers with data processing	C_7^2	[11]
	Issue of removing noise while preserving anomalies in IoT data	Problems related to noise removal in existence of potential anomalies in IoT sensor data in manufacturing	C_8^2	[15]
Scalability and Flexibility (C3)	Lack of standardization	Standardization in IoT helps in decreasing overall maintenance cost	C_1^3	[3]
	Huge investment	Huge investment in establishing IoT based maintenance systems	C_2^3	[3, 5]
	Limited scalability of maintenance data transfer and processing	Scalability of data transfer and processing helps in remote maintenance monitoring	C_3^3	[11, 14]
	Lack of flexibility in reconfiguring production processes	Flexibility in reconfiguring production processes helps in complex decision making related to IoT based maintenance	C_4^3	[9]
	Heterogeneity of underlying machinery and enabling technologies	Heterogeneity of underlying machinery and enabling technologies helps in smooth IoT based maintenance	C_5^3	[3]

(continued)

Table 1 (continued)

Dimension	IoT challenges	Description	Code	References
	Reduced downtime due to machine faults	Decrease in downtime due to machine faults is the challenge in IoT maintenance monitoring	C_6^3	[16]
Security (C4)	Cybersecurity and data security	Cyber security and data security is required in IoT based maintenance	C_1^4	[3, 7, 11, 14]
	Safety issues	Safety issues refers to the insecure interfaces, poor IoT device management, lack of maintenance data protection etc	C_2^4	[17]
	Storage issues for handling big maintenance data	Lack of storage systems for handling big data in maintenance	C_3^4	[15]
	Security weaknesses in embedded devices	Security issues in embedded devices under maintenance	C_4^4	[6]

2.1 Research Gaps

Previous studies presented various challenges associated with industrial IoT/IoT adoption in manufacturing industries. The previous research has shown a significant contribution in recognizing the challenges, benefits, and opportunities associated with maintenance in manufacturing industries. To the best knowledge of authors, very few studies were reported in analyzing IoT challenges with respect to maintenance monitoring from different dimensions, namely, connectivity, data management, security, etc. Moreover, no concrete research has been done on analyzing the challenges of IoT with respect to maintenance monitoring using modelling approaches. Thus, in the present study, an attempt has been made in recognizing several challenges from different dimensions associated with IoT-enabled maintenance monitoring and analysis using Graph theory approach.

3 Methodology

The present study begins with defining the scope of the study followed by extraction of relevant literature and identification of influential IoT challenges with regard to maintenance monitoring. IoT challenges have been finalized through industrial and academic experts' opinions possessing over 10 years of experience in the intelligent manufacturing domain and planning to deploy IoT in maintenance-related activities. Further, the challenges of IoT adoption regarding maintenance monitoring have been analyzed using Graph Theory methodology. The graph theory approach possesses several advantages over other modelling techniques. It aids in understanding the system likened to other approaches such as analytical hierarchy process, interpretive structural modelling, etc. [4]. Moreover, the graph theory approach allows converting the diagrammatic representation into the matrix, which further helps in performing mathematical computations. The key steps of the Graph Theory approach are diagraph representation, matrix formation, and Permanent representation [18]. Diagraph representation refers to the development of diagraph or graphical representation to depict the interrelationship amongst identified challenges using a group of nodes and directed arcs. Further, to measure the intensity of challenges interrelationships, the diagraph is converted into a matrix using the variable permanent matrix (VPM) that quantifies the interrelationship and provides a single numerical value known as permanent of matrix. Finally, the permanent of matrix is computed denoting the intensity value of challenges. The Graph Theory procedure can be referred from Jayakrishna et al. [18].

4 Case Study

The case study has been carried out in a manufacturing organization involved in production of automotive component situated in Tamilnadu, India. To begin with its adoption, the organization is aiming on adoption of IoT in maintenance related activities. However, there exist several challenges in IoT about maintenance of machines. Therefore, to help them with the smooth adoption of IoT in maintenance monitoring, this study formulated a structural-based problem of identifying the potential IoT challenges in four different dimensions and analyzed the interrelationship amongst dimension and its respective challenges using Graph Theory approach. The consensus opinion of inputs is taken from five industrial experts and academic researchers possessing experience of more than 10 years and having expertise in industrial equipment maintenance and automation. Twenty-four potential challenges concerning IoT adoption and implementation in maintenance monitoring from four different dimensions have been identified. The implementation of graph theory is required to build VPM using the calculation of the permanent value of individual matrix based on which best and worst possible case could be determined. The permanent of the matrix (per) is similar to the determinant of the matrix but with positive sign everywhere. The diagonal components of VPM-IoTch (variable permanent matrix of IoT challenges) signifies the degree of importance of each dimension of IoT challenges. VPM for IoT challenges are calculated using Permanent function. VPM of all challenges is denoted by VPM- C1 (VPM1), VPM – C2 (VPM2), VPM – C3 (VPM3), and VPM – C4 (VPM4). Figure 1 represents the diagraph for dimensions with respect to IoT challenges.

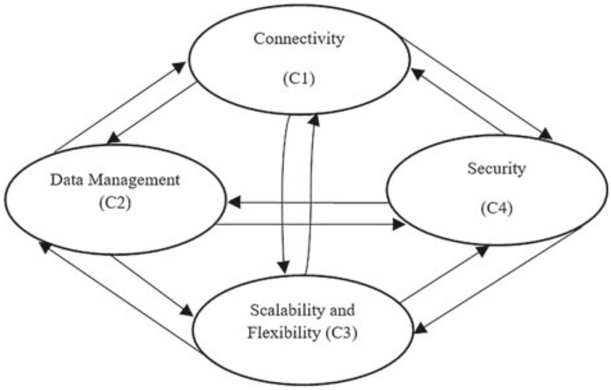

Fig. 1 Diagraph for dimensions with respect to IoT challenges

A. Developing VPM

$$\text{VPM - IoTch} = \begin{bmatrix} C_1 & c_{12} & c_{13} & c_{14} \\ c_{21} & C_2 & c_{23} & c_{24} \\ c_{31} & c_{32} & C_3 & c_{34} \\ c_{41} & c_{42} & c_{43} & C_4 \end{bmatrix} \quad (1)$$

The elements of the above matrix (Eq. 1) are computed using the diagraph (as shown in Fig. 1). The diagonal elements signify the nodes of the diagraph, here it is the dimensions of IoT challenges related to maintenance monitoring. The diagonal element value (inheritance of challenges) is decided by the experts using scale 1–9 (1—Extremely low, 3—Low, 5—Average, 7—High, 9—Extremely High) [15]. The non-diagonal elements represent the extent of relationship between the dimensions. The non-diagonal element value (interdependencies of challenges) is decided by the experts using scale 1–5 (1—Very Low, 2—Low, 3—Average, 4—High, 5—Extremely High) [15]. The variable permanent matrix (VPM) is utilized to compute the permanent value of the matrix. Here, all the computations of permanent value are carried out using MATLAB software. Figure 2 represents the diagraph for individual dimensions with respect to its corresponding IoT challenges. The diagraph denotes the interrelationships of IoT challenges for each dimension based on which the variable permanent matrix is computed. The base formula for calculating permanent value of 5 × 5 matrix can be found in Attri et al. [4].

B. Computing permanent values for VPMs

The permanent values of all the diagonal elements of matrix shown in Eq. 1 are evaluated using the variable permanent matrices as shown in Eqs. 2–5.

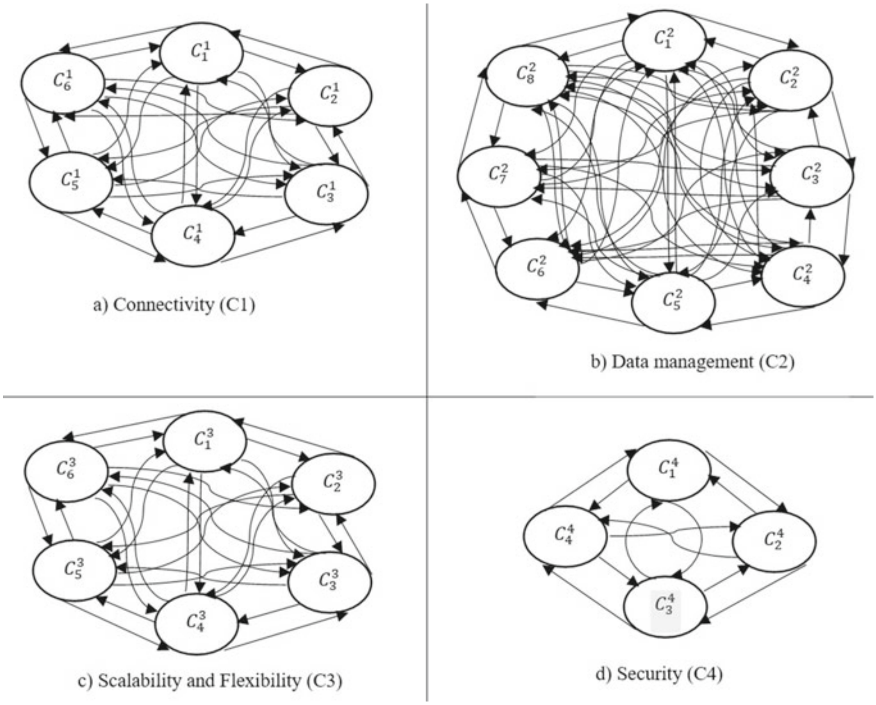

Fig. 2 Diagraph for IoT challenges: **a** Connectivity (C1); **b** Data management (C2); **c** Scalability and flexibility (C3); **d** Security (C4)

$$\text{VPM} - \text{C1(VPM1)} = \begin{bmatrix} 8 & 4 & 4 & 4 & 3 & 3 \\ 4 & 7 & 3 & 4 & 4 & 4 \\ 3 & 3 & 6 & 3 & 4 & 3 \\ 4 & 4 & 3 & 8 & 4 & 4 \\ 4 & 3 & 2 & 4 & 7 & 3 \\ 3 & 4 & 3 & 4 & 4 & 6 \end{bmatrix} \tag{2}$$

per (VPM1) = 3,627,938.

$$\text{VPM} - \text{C3(VPM3)} = \begin{bmatrix} 6 & 3 & 3 & 3 & 3 & 3 \\ 4 & 8 & 3 & 4 & 3 & 0 \\ 3 & 4 & 7 & 4 & 3 & 3 \\ 4 & 4 & 3 & 8 & 4 & 3 \\ 3 & 4 & 3 & 3 & 7 & 4 \\ 3 & 3 & 3 & 3 & 3 & 7 \end{bmatrix} \tag{3}$$

per (VPM3) = 2,618,313.

$$\mathrm{VPM} - \mathrm{C4(VPM4)} = \begin{bmatrix} 7 & 4 & 3 & 4 \\ 4 & 6 & 3 & 4 \\ 3 & 2 & 7 & 2 \\ 5 & 3 & 2 & 5 \end{bmatrix} \tag{4}$$

per (VPM4) = 6736.

Finally, using the permanent values computed above for all VPMs, the final VPM-IoTch is calculated as shown in Eq. 5.

$$\mathrm{VPM} - \mathrm{IoTch} = \begin{bmatrix} 3627938 & 3 & 3 & 4 \\ 4 & 1872424240 & 3 & 4 \\ 3 & 3 & 2618313 & 3 \\ 4 & 4 & 3 & 6736 \end{bmatrix} \tag{5}$$

Per (VPM – IoTch) = $1.198085335 \times 10^{26}$.

5 Results and Discussions

The present study analyzed the IoT challenges in maintenance parameters monitoring using GT methodology, which helped to gain the intensity/influence of several challenges of IoT in maintenance adoption in automotive industries. The findings of the study revealed that the IoT challenges with regard to “Data management (C2)” dimension influence more, whereas “Security (C4)” dimension influence less to the maintenance monitoring in Industry 4.0 environment. From this, it may be concluded that the IoT challenges “Data integration”, “Inflexible maintenance data collection”, “Lack of high quality of maintenance metadata”, “Available data not fit for the purpose of IoT based maintenance”, “Data fragmentation and lack of interoperability across different datasets”, “Lack of awareness about maintenance monitoring”, “Lack of tools to support developers with data access and processing” and “Issue of removing noise while preserving anomalies in the IoT data” needs more attention by the industrial manufacturers. Next major dimension is found to be “Connectivity (C1)”. In order to handle these challenges, the industrial practitioners and managers should focus on improving connectivity between machines and sensors using IoT system. Correspondingly, the practical best-case and practical worst-case values of each IoT challenges dimension are calculated. Table 2 shows the current, best, and worst values of permanent function for each IoT challenge at system and sub-system level. These values will help the industrial manufacturer to self-assessment of organization in determining the influence of IoT adoption in maintenance monitoring.

Table 2 Current, best, and worst values of permanent function

IoT challenges dimension	Current level of influence		Practical best case		Practical worst case	
	Permanent	Log10	Permanent	Log10	Permanent	Log10
per (VPM1)	3,627,938	6.559	6,551,784	6.816	667,952	5.824
per (VPM2)	1,872,424,240	9.272	3,541,831,278	9.549	325,064,574	8.512
per (VPM3)	2,618,313	6.418	4,693,014	6.671	379,854	5.560
per (VPM4)	6736	3.828	15,344	4.186	1216	3.084
Per (VPM – IoTch)	$1.198085335 \times 10^{26}$	26.078	$1.671005502 \times 10^{27}$	27.223	$1.002917461 \times 10^{23}$	23.001

6 Practical and Managerial Implications

The unpredicted breakdown in automotive industries results in huge loss in terms of profit and production. Thus, if the breakdown condition is known well in advance, zero downtime can be attained. The recommended influence order of dimensions in this study would help industrial managers to focus on the dimension for smooth adoption of IoT in maintenance parameters monitoring. Considering the application of IoT, the present study has great industrial relevance. The computation of the influence of IoT challenges is very useful in tackling the challenges and achieving zero downtime. For instance, the industry practitioners can utilize the findings of the study in understanding the challenges of IoT in maintenance monitoring for each dimension and establishing IoT-based maintenance system which in turn provides reliable information on machine maintenance remotely, thereby assisting in achieving zero downtime. The present study recommended industry practitioners and managers to focus on data management to understand the maintenance issues in advance to improve the production output.

7 Conclusions, Limitations, and Future Research Directions

The present work attempts to measure IoT challenges in maintenance parameters monitoring in automotive industries through a systematic structural GT approach. The present study helped in modelling the interdependencies amongst various challenges and denoted by a single numerical value, i.e., permanent value. The findings of the study revealed that IoT challenges regarding the "Data management (C2)" dimension influence more, whereas the "Security (C4)" dimension influences less to the maintenance monitoring in Industry 4.0 environment. The influence order of IoT challenges regarding maintenance monitoring is as follows:

Data management (C2) > Connectivity (C1) > Scalability and Flexibility (C3) > Security (C4).

In the present study, four major dimensions are recognized for evaluation of influence of IoT challenges in maintenance parameters monitoring. In future, other dimensions may be considered for the analysis. The proposed methodology has certain limitations in handling more significant number of challenges due to the combinatorial approach, which can be overcome using the development of software to handle more significant number of dimensions/challenges. One more limitation of the research is the use of limited expert opinion to obtain the inheritance and interrelationships values for IoT challenges. In future, more number of experts may be involved or trail studies using survey analysis may be performed to understand the deeper insights on IoT challenges in maintenance monitoring. Further, future researchers may think of developing decision support system to assist the organization in handling complex manufacturing processes.

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Machine Learning Techniques for Smart Manufacturing: A Comprehensive Review

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1 Introduction

Artificial intelligence (AI) and especially machine learning (ML) is getting popular among manufacturers to resolve unexpected machinery failure or defective product delivery. Manufacturers can improve operational efficiency, customize product designs and efficiently plan future financial actions using AI and ML techniques. The production process gets affected by several variables and is full of analytical data that can be effectively analyzed using ML models to obtain the effect of individual variables. With AI systems, manufacturers efficiently schedule maintenance and repair of equipment to avoid pre-mature or catastrophic failures.

Nowadays, ML algorithms are prominently used for the parametric designing of components. This concept is known as the generative design wherein a family of all the possible design outcomes is generated with generative design software for the given manufacturing methods, materials, size, weight, strength, and cost constraints. The data sets collected from sensors on machines are effectively analyzed by edge analytics to improve the quality of manufacturing parts.

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ML is a method of data analytics and a branch of artificial intelligence that permits the machine to learn from the data on its own and to make and perform decisions or predictions. Over the past few years, ML is widely gaining its popularity in manufacturing for material property prediction [1–3], distortion and failure predictions, smart manufacturing [4–6], natural language processing, and object recognition. With the increase in technological advancements in sensors and other electronic components, the machines are now observed and equipped with various sensors and communication devices which has shown significant potential to improve the process, reduce the operational times, enhance the product quality and improve the level of automation. Recent studies show that 82% of companies using smart manufacturing methods employed with ML techniques have resulted achieving increased efficiency and 45% of companies have resulted in achieving high customer satisfaction for their manufactured parts [7].

Machine vision technology is successfully used to detect defective products. ML techniques are also effectively used in inventory planning activities. In general, AI technologies help manufacturers to optimize production processes for better quality products at right time and at reducing costs. Extensive research done on ML in manufacturing is focused on classification, developing models, and using various classification approaches. The classification approaches mainly used are instance-based learning [8, 9], genetic algorithms [10], decision-tree induction, and Bayesian learning algorithms., etc. In light of the above advantages, this paper aims to provide a state-of-the-art review of various machine learning techniques that have been implemented in welding, molding, machining, and forming processes.

2 Welding

Welding is a process of fabrication where two or more metals are joined together by using heat. ML can be used in welding for various purposes like predicting the weld pool temperature, detecting the defects in welding, analyzing the weld pool, deciding process parameters, etc. In this section, researchers' works on the applications of various ML techniques for arc welding, laser welding, gas welding, ultrasonic welding, and friction stir welding are discussed.

Sarkar et al. [11] predicted and analyzed isotherms in submerged arc welding. An infrared camera was used to obtain the thermal data of the sample. Programs were written in MATLAB to generate transient state isotherms and to obtain local temperature, temperature–time curve, temperature field map. Zhang et al. [12] during single bevel gas metal arc welding used a CNN (Convolutional neural network) model to predict burn through and weld depth of weld pool. An accurate online detection of weld defect was done in robotic arc welding using CNN and weld images. Images acquisition system was developed. Nomura et al. [13] used a classification model for burn-through prediction and a regression model to predict the weld depth. The machine learning model efficiency was observed to be 95% for errors less than 1 mm. Identifying real-time seam defects in robotic arc welding was possible using an integrated learning model and optical spectroscopy. Principal Component Analysis (PCA) was applied to the arc spectrum for disclosing the hidden mechanism in the dynamic welding process [14].

Attempts have been also made to predict the weld depth for high-strength aluminum alloys using a Beta-Variational-Autoencoder (β-VAE) model that was used to train the database [15]. The increasing demand for power batteries has even though boosted the automotive industry; the safety of power batteries is becoming an imminent problem. Quality inspection of laser welding for the safety vent of power batteries is a major issue. Yang et al. [16] proposed a transfer learning technique using CNN and a pre-trained squeeze-net model with a small model size and low computation complexity to identify the defect in the laser welding of the safety vent of power batteries.

A deep learning technique was used to discover the weld defects with multiple optical sensors during disk laser welding of thick plates. A multi-sensor system was designed to capture signals of the welding status during high power disk laser welding. A CNN algorithm was used for the online prediction of weld defects using a multi-sensor system [17]. Liu et al. [18] while dual-beam laser welding of 316L austenite stainless steel used a Taguchi approach with artificial neural networks (ANN) and genetic algorithm (GA) to obtain the optimum welding parameters. The welding parameters were optimized for higher yield strength of the welded joint by the back-propagation neural network (BPNN) algorithm based on the porosity number, the average area of porosity, and weld width in laser weld beads.

Cheng et al. [19] predicted the weld penetration for gas tungsten arc welding (GTAW) by detecting dynamic development of weld pool using ML technique. This was done by developing composite images of the weld pool and by using a CNN algorithm. The test showed an accuracy of about 97.5%. They used a visible spectrum with the state-of-the-art approach for image classification to detect defect in the TIG welding process. Spectrum HDR camera was used by them for gathering images of the weld pool. ANN model was developed by them to classify welding defects with an overall accuracy of 93.4%.

Satpathy et al. [20] developed regression model, artificial neural network (ANN), and adaptive neuro-fuzzy inference system (ANFIS) for predicting and simulating the joint strength of the ultrasonic welded Al-Cu sheets. They investigated the effect of vibration amplitude, weld pressure, and weld time on the tensile shear and T-peel failure loads. Their study found better accuracy with the ANFIS model and thus it could be used to predict the weld strength in USW process. Suresh et al. [21] performed the optimization of process parameters of friction stir spot welding of AA6061-T6 with the addition of Al_2O_3 nanoparticles into the guide holes. The optimization was performed using a newly proposed NSTLBO-MLPs algorithm and six other metaheuristic search algorithms. Their results showed that the NSTLBO-MLPs algorithm delivers the most accurate performances by generating uniformly distributed Pareto fronts with the highest numbers of non-dominated solutions for all data set sizes.

It has been observed that ML techniques are helpful in increasing the efficiency and accuracy of welding processes by optimizing the process parameters using neural networks. ML techniques are successfully used for visualizing weld quality using regression analysis. ML techniques such as the deep learning method were observed as helpful in classifying the welded specimens into good weld and weld with lack of fusion and burn through. However, this study finds scope for further research on classification and defect detection and its dimensions in welds.

3 Molding

Molding is the process of manufacturing by shaping liquid or pliable raw material using a rigid frame called a mold or matrix. ML is extensively used in molding to predict defects, analyzing various parameters, etc. In this section, a group of researchers works on the ML techniques for injection molding, liquid composite molding, and blow molding are discussed.

Finkeldey et al. [22] presented a new way for training an ML-based model that subsumed simulation data to minimize the number of physical experiments. The selection of simulation data for process parameters that would result in the highest prediction accuracy was made methodologically. A similarity analysis between measured and simulated data was used to select the data. The ML-based model was trained to predict the similarity between measured and simulated data. A new smart control method for cyclical control of the ram velocity in the injection molding machine was developed using a feedback–feedforward signal configuration. An iterative learning algorithm was used for this purpose. PI and ILC controls are tuned by a simulation study that significantly improved the performance of the technique [23]. Lee et al. [24] proposed a system framework, functions, and data flow for the smart factorization of injection mold process for industry 4.0. This factory could find local or global optimized solutions for the injection molding system and accumulate know-how, which can be used to anticipate future abnormal symptoms. A real-time data acquisition was implemented for this purpose.

X-ray computed tomography for the computation of reinforcement permeability for liquid composite molding processes was reported by Ali et al. [25]. The critical issues with the XCT technique are sample size restrictions, temporal resolution, and noise. Their study depicted three modeling approaches for permeability computations which differ significantly in terms of implementation and accuracy. They observed the voxel model being realistic was an accurate representation of the complex fabric architecture. However, the voxel model may need some clean-up steps. The other two models used were the stochastic virtual model and the simplified geometry model.

Huang and Liao [26] elaborated a neural network-based model approach to investigate the effects of the die temperature and flow rate on the diameter and thickness swells of the parison in the continuous-extrusion blow molding of high-density polyethylene (HDPE). Neural network model predictions were compared with actual experimental readings. Their study observed that preform temperature played a vital role in injection stretch blow molding of plastic bottles. Yang et al. [27] applied a radial basis function (RBL) neural network to optimize the lamp settings used in the oven for injection stretch blow molding. Their work combined a two-stage selection algorithm with particle swarm optimization (PSO). The simulation results from their study had confirmed its feasibility and accuracy and could be used to optimize the lamp settings in the oven.

ML techniques such as ANN, in particular Multilayered Perceptron (MLP), and Decision Trees have been successfully used for process optimization and real-time process monitoring of injection molding. However, further research is required on the plastic injection process monitoring using advanced tree-based algorithms and diverse neural networks architectures with classical regression algorithms.

4 Machining

The ML techniques in the machining processes assist in increasing the productivity rates, monitoring the proper maintenance of the system, improving the product quality, and optimizing the design and process parameters. Artificial intelligence helps us to produce largely customizable goods with better quality at lower costs. In this section, researchers work on the ML techniques for turning, milling, drilling, grinding, finishing, and electric discharge machining (EDM) are discussed.

Cho et al. [28] developed a tool breakage detection system to reduce the time required for repairing and maintenance. The support vector machine learning algorithm was utilized, in which the multiple forces and the power utilization was recorded with the help of sensors. The model developed was more precise than the traditional one. Traini et al. [29] developed a framework to detect the tool wear for preventing the breakdown. Saadallah et al. [30] presented a framework-built model for automatically adjusting the process parameters to ensure a stable process.

Saving resources and time with assuring and maintaining product quality is of prime importance to manufacturing industries. In turning operation, ML techniques could be useful for the selection cutting tool, cutting parameters (cutting speed, feed, and depth of cut), cooling environment, etc., to obtain the optimum machining performance. Moghadaszadeh et al. [31] investigated various ML methods to estimate tool life. Their study used the Bayesian method in a case similar to previous data available and the Taylors equation when only features, property, and condition data were available. Lutza et al. [32] developed a service-based system proving that the torque of the passive force axis is a suitable data source for assessing the machinability of material. Their study concluded that the support vector machine gives the desired results based on the coefficient of determination.

Saranya et al. [33] presented an approach for cutting tool selection and process parameters optimization using neuro-fuzzy and Genetic algorithms. Homami and Tehrani [34] conducted various experiments and developed the models using AI neural networks and genetic algorithms. Their study observed that with the increase in the nose radius, the tool strength increased, the flank wear was reduced by 36.8%, and surface roughness decreased by 32%. Jurkovic et al. [35] studied three ML methods to predict cutting parameters in turning. Their study found that the SVR polynomial kernel was an accurate and superior technique compared to the linear kernel and RBF kernel. Additionally, the SVR and polynomial regression showed similar performance.

Issues in drilling such as stick–slip vibration/hole cleaning, loss of circulation, excessive torque and drag, low rate of penetration (ROP), drill bit wear can be monitored and prevented using ML techniques. Elkatatny [36] formulated an equation for the ROP prediction in real-time using ML and AI neuro-fuzzy systems, ANN, and the SVM. The drill bit design and TFA were taken as input variables. It was seen that ANN has more accuracy than other techniques. Gurina et al. [37] developed an irregularity alarming model for directional drilling in which the past accidents data was compared with the ongoing drilling for the analysis of similarity, and hence to obtain, the deviations. Bustillo et al. [38] developed a model to predict and optimize the high-speed deep drilling process with MQL and conventional working fluid. The Bayesian networks were used to predict the cooling system, tool, and cutting parameters. Kottner et al. [39] developed ANN, linear regression, and decision tree models to predict and monitor drilling performance.

Attempts have been also made in optimizing the EDM process parameters that influence the final product using various ML techniques [40, 41]. Paturi et al. [41] analyzed the EDM of Inconel 718 by developing support vector machine (SVM), response surface methodology (RSM), and artificial neural network (ANN) models. Their study observed better accuracy in the predicted results by SVM and ANN models compared to the RSM model.

ML techniques also find their successful applications in the optimization of finishing processes for precise and accurate components. Pandiyan et al. [42] revied the AI and signal processing techniques used in the abrasive finishing processes. They reported defects and key features of different abrasive finishing processes. Their study observed that AI could be successfully explored for monitoring and modeling the abrasive finishing processes. ML techniques assisted in the grinding process to produce better quality components with minimum operator intervention and more flexibility. Rowe et al. [43] reviewed the possibility for integration of AI in grinding for the selection of parameters and developing self-decision-making systems to assist the process. Lezanski et al. [44] developed a neuro-fuzzy algorithm for the condition monitoring of the grinding wheel.

ML techniques in machining are useful in cost and time savings, improving product quality and productivity rates, and waste reduction. ML techniques, namely, polynomial regression (PR), support vector regression (SVR), and Gaussian process regression (GPR) were used to predict machining performance. However, ANN is the most commonly used ML technique. However, the development of a metaheuristic approach-based ANN algorithm is required for efficient multi-objective optimization of process parameters. Also, there is scope for the development of a data-driven industrial surface quality diagnosis for the machining processes for difficult-to-cut materials using supervised machine learning methods.

5 Forming

In the forming, components undergo plastic deformations and acquire required shapes and sizes by applications of suitable stresses such as compression, shear, and tension. With the application of ML in the forming operations, the components can be produced with higher accuracy and precision. In this section, a group of researchers works on the applications of various ML techniques to conventional forming (rolling, extrusion, and drawing), and the special forming processes (incremental forming, powder forming, and hydroforming) are discussed.

In rolling specific shape is obtained by passing a metal strip between the two rollers. The rolling force and rolling torque, the velocity of rolls, and angle of contact, and power requirements are the process parameters. ML techniques can be used to predict and optimize the rolling force and other process parameters to obtain maximum process efficiency. Several attempts have been made to develop ANN models to predict the rolling force. Variable learning rate and conjugate gradient technique was used for training the network for better accuracy of the predicted results [45].

ML also finds successful application in the extrusion process that is used to create objects of a fixed cross-sectional profile. ML can be used to predict extrusion force and overall monitoring of the process. Li et al. [46] presented various ML-based models to predict surface roughness during extrusion-based additive manufacturing. The models were trained with six ML algorithms such as random forest (RF), AdaBoost, classification and regression tree (CART), support vector regression (SVR), ridge regression (RR), and random vector functional link (RVFL) network. Multiple sensors were used for collecting on-time condition monitoring data. Their experimental results showed that the predictive models trained by the ensemble learning algorithm are capable of predicting surface roughness of 3D printed parts in real-time given condition monitoring data and surface roughness measurements.

In incremental forming, a sheet is formed by a series of small incremental deformations. Möllensiep et al. [47] developed an ANN model to predict and optimize the geometrical accuracy of automated incremental sheet forming. Akrichi et al. [48] applied shallow learning and deep learning techniques for predicting geometrical accuracy in the single-point incremental forming process. The back-propagation neural network with one hidden layer was selected as the representative for shallow learning and the deep belief network and stack autoencoder were selected as the representatives for deep learning. The sheet thickness, tool path direction, step depth, speed rate, feed rate, and wall angle were selected as the process parameters. The results of their studies indicated that deep learning could be a powerful tool for predicting geometric accuracy in single-point incremental forming. Further, they found that the deep belief network model achieved superior performance accuracy for the prediction of roundness and position deviation in comparison with the stack autoencoder approach.

The process parameters in powder manufacturing must be optimized to produce high-quality powders with desired sizes depending on their use. Lou et al. [49] investigated the application of the core/shell technique to improve powder compactability. They performed experiments to evaluate the effects of the type of core and shell materials and their concentrations on tensile strength and brittleness index. Six ML algorithms were used by them to model the relationships of product profile outputs and raw material attribute inputs. they are response surface methodology (RSM), support vector machine (SVM), and four different types of artificial neural networks (ANN), namely, backpropagation neural network (BPNN), genetic algorithm based BPNN (GA-BPNN), mind evolutionary algorithm based BPNN (MEA-BPNN), and extreme learning machine (ELM). Their study observed that all ML techniques provided acceptable predictability and capability of generalization. However, the ANN algorithms were shown to be more capable of handling convoluted and non-linear patterns of two datasets.

Researchers also attempted ML techniques in the hydroforming process. It is a specialized type of die forming that uses high-pressure hydraulic fluid to form the work material. ML techniques were used to improve the quality of the product and reduce the prototyping cost. Lorenzo et al. [50] integrated AI techniques, numerical simulations, and experimental knowledge to carry out tube hydroforming design. A fuzzy system was integrated with a FEM code for process simulation in the process design phase. Steinhagen et al. [51] described an approach to quickly analyze and optimize hydroforming processes using learned data of standard processes and their statistic variances. Since unsupervised machine learning approaches were applied, the algorithm needed only a few runs to learn the data of standard processes. Their study also introduced algorithms that automatically detect and classify workpiece defects, monitor the wear of hydraulic valves, and optimize the energy consumption of the hydraulic pumps.

From the literature reviewed, it has been observed that a group of researchers has successfully used ML techniques to predict springback as it influences the quality of sheet metal forming products. However, demand for the use of advanced high-strength sheet metals in the automotive industry is increasing. These high-strength materials have less formability and increased sensitivity of the springback. And, hence, it is necessary to develop ML neural network models as an expert system to predict springback in sheet metal forming.

6 Conclusion

Artificial intelligence (AI) and especially machine learning (ML) is getting popular among manufacturers to resolve unexpected machinery failure or defective product delivery. Manufacturers can improve operational efficiency, customize product designs and efficiently plan future financial actions. The main aim of implementing the ML techniques being to save time, cost, resources and avoid possible waste generation. This paper presents a systematic review focusing on the application of various

ML techniques to welding, molding, machining, and forming processes. This review has shown that AI and ML technologies assist manufacturers to optimize production processes for better quality products at right time and at reducing costs. Extensive research on applications of ML techniques in manufacturing was focused on classification, development of ML models, and using various classification approaches such as instance-based learning, genetic algorithms, decision-tree induction, and Bayesian learning algorithms. A convolutional neural network (CNN) model could be used to predict burn through and weld depth of weld pool. Artificial neural networks (ANN), genetic algorithm (GA), and adaptive neuro-fuzzy inference system (ANFIS) were successfully used to obtain the optimum process parameters. ML algorithms such as random forest (RF), AdaBoost, classification and regression tree (CART), support vector regression (SVR), ridge regression (RR), response surface methodology (RSM), support vector machine (SVM), and random vector functional link (RVFL) network widely used for process improvement. All ML techniques provided acceptable predictability and capability of generalization. However, the SVM and ANN algorithms were reported to be more capable of handling convoluted and non-linear patterns of two datasets.

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Data Acquisition and Data Visualization Framework for Smart Manufacturing

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1 Introduction

Industry 4.0 is a broad term that encapsulates both the ongoing and the oncoming advancements in the field of manufacturing industry. Its concept is based upon the four pillars of Manufacturing, Business, Product and Customer [1]. The enabling technologies under this umbrella-term are concerned with one or more of these pillars.

Being one of the fundamental components of Industry 4.0, manufacturing systems have evolved from originally being completely manual and human-labor dependent to computer automated, and then eventually into connected systems through the use of information technology [2]. This transition from individual hardware to digitally connected systems has been at the pith of the fourth industrial revolution.

A key characteristic of these smart manufacturing systems is the ability to monitor different aspects of the overall process, which include machine operation, maintenance and production. This has been enabled through widespread deployment of embedded sensors which act as data sources for real-time monitoring. Consider an example where different types of metrics are being monitored on a machine such as vibrations, temperature, speed, feed and energy consumption. Each of these is measured using different types of sensors, and this data is then sent further for monitoring.

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In manufacturing, real-time monitoring is concerned with reducing the time gap between the occurrence of an event in the process and the transfer of insights from this event to the concerned users. The main goal of all the monitoring implementations is then to reduce this latency, known as insight latency, which could lead to a direct reduction in economic cost. Key enabling technologies for this purpose are those of Industrial Internet of Things and Cloud-based monitoring.

This contribution aims to provide a general implementation framework that could be employed in a manufacturing system to reduce Insight Latency. This is accomplished through data acquisition and visualization of the collected data. The distinguishing factor of this contribution is its use of MATLAB App Designer for data aggregation and real-time data visualization in smart manufacturing environment. In this approach, both data acquisition and visualization are implemented using different applications, but on the same physical machine.

Figure 1 shows the proposed system architecture. Data from the field devices could be made available at the host machine using a variety of standard communication protocols from different manufacturers. This selection is left upon the user. For proof-of-concept purpose, a Modbus TCP implementation example is covered later in this text. Communication between these data acquisition and the data visualization stages play an important role and should follow the current interoperability standards under Industry 4.0. This requirement is fulfilled by adoption of OPC Unified Architecture for data transfer between these two stages. The resulting data visualization application is deployed on a local network which gives different authorized users access to the process data.

Thus, by deployment of the above architecture, monitoring of the manufacturing process in real-time could be achieved. The information acquired is contextualized before its presentation to the user according to pre-defined user roles. This eliminates information redundancy and provides increased value to the user.

This paper is divided into six sections. In Sect. 1, introduction was covered. Section 2 covers the Data Acquisition stage while client–server communication is dealt under Sect. 3. Data Visualization is discussed in Sect. 4 followed by Sect. 5 that covers the Intranet deployment. Section 6 is dedicated to conclusion and future work.

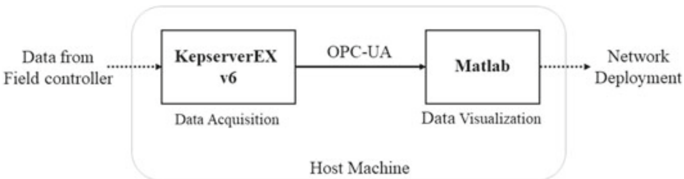


Fig. 1 System architecture

2 Methodology

A sequential approach is undertaken in this project where the complete implementation is divided into four individual steps—Data Acquisition, OPC-UA Communication, Data Visualization and Intranet Deployment. Successful execution of these steps yields the observed results.

2.1 *Data Acquisition*

KepserverEX v6, referred to as Kepserver hereafter, is a connectivity platform that acts as an interface between the incoming data from the field devices and the client application running on the host system [3]. The main advantage of including such an application in our architecture is that it provides a single contact point to the client application irrespective of the number of physical devices provisioned and their individual communication protocols. It features a very large selection of device drivers to connect with controllers from different manufacturers using different protocols. Apart from the physical device drivers, Kepserver has a provision of simulation driver that simulates the presence of a physical device. The client is also offered numerous options in terms of obtaining process data from the server. These include Classic OPC, OPC-UA, IT protocols like MQTT, and proprietary protocols like FastDDE and GE NIO. In a networked system with multiple controllers, server allows to configure the frequency of communications in order to balance the load when the network demand throttles.

On the client side, this implementation uses OPC-UA to establish communication between Kepserver and MATLAB. There are two possible implementations when it comes to the type of driver to be used with the server.

Smart Lathe Machine. A channel in Kepserver denotes the physical media and its associated protocol used by the field controller to communicate with the server [4]. Considering the example of the smart lathe machine, its PLC uses Modbus TCP/IP for data communication, and thus the channel used in the Server would be configured with a Modbus driver. Figure 2 shows the connection of PLC with the host machine. A point to note here is that this is an Intranet deployment and the application has not

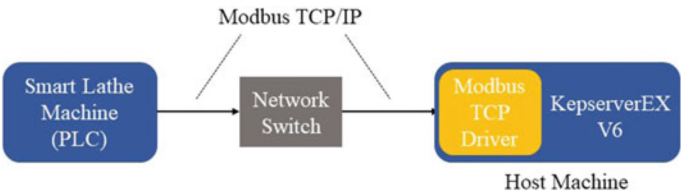


Fig. 2 A possible deployment architecture with a hardware device for Data Acquisition

been made available on the public network due to security reasons. Network switch connected to the PLC ensures successful communication at the Data Link layer of the OSI model. It uses MAC address to forward the packet to its destination within the local network.

Simulated Data. Kepserver features an additional driver for simulation that allows for generation of different types of standard signals according to the values provided by the designer. This project makes use of this driver to simulate data coming from the physical machine. Three types of simulation functions have been used, namely, Ramp, Random and User. Ramp function simulates a ramp signal with a pre-defined slope while the Random function generates random values of integer or float data types within a specified range. User function allows to iterate through a list of string values [5]. Interfacing of the simulation driver is same as that of Modbus driver, except for the fact that a different option is selected in this case and the hardware device is absent. Hence, its figure is omitted.

2.2 OPC-UA Communication

The exchange of information between Client and Server takes place according to the OPC Unified Architecture specification. Unified Architecture builds upon the information model of the Classic OPC standard, and extends it to include vendor-specific extensions along with the specifications of third-party organizations like ISA, IEC, etc. [6]. OPC-UA standard defines protocols for Data Access, Alarms and Conditions, Historical Analysis and Programs under the category of base OPC stack.

OPC-UA server, which in this implementation is Kepserver, makes its address space available to the client application for data transfer [7]. Nodes are the fundamental component of this address space and in the argot of Kepserver, these are termed as Tags. Each tag represents an abstract or a physical value, and has a data type value associated with it, along with its address in the address space. Because information modelling in this standard allows for nodes to include references to other nodes, a complex hierarchy could be generated that represents physical or logical relations between these nodes [8]. In fact, a default hierarchy is automatically generated by the Server upon its execution, which consists of default system tags and Channels. For this implementation, all the simulator devices representing individual Smart Lathe machine were modelled under a single channel. The server makes use of port 49,320 on the local machine to serve as an endpoint for communication.

MATLAB acts as the OPC-UA client in this project, and thus reads data from the server's address space. This is accomplished using a five-step approach in MATLAB script. The first step is to create an OPC-UA object by passing local port number to the OPC UA function. This created object is then passed to the connect function which connects with the server. In this implementation, anonymous authentication scheme was used, but a basic username-password scheme, and authentication using digital certificates is also supported under OPC-UA. The third step is to create a node array in MATLAB so that in the subsequent stages of the program, navigating the address space, or namespace, of the Kepserver is possible. In order to read a specific node value, the concerned node's object needs to be created. This is done in the fourth step. Finally, the node object is passed into the read value function which returns the node's latest value (Fig. 3).

2.3 Data Visualization

After the establishment of communication, MATLAB is able to read node values as specified in the script. This makes it possible to provide visualizations to the user

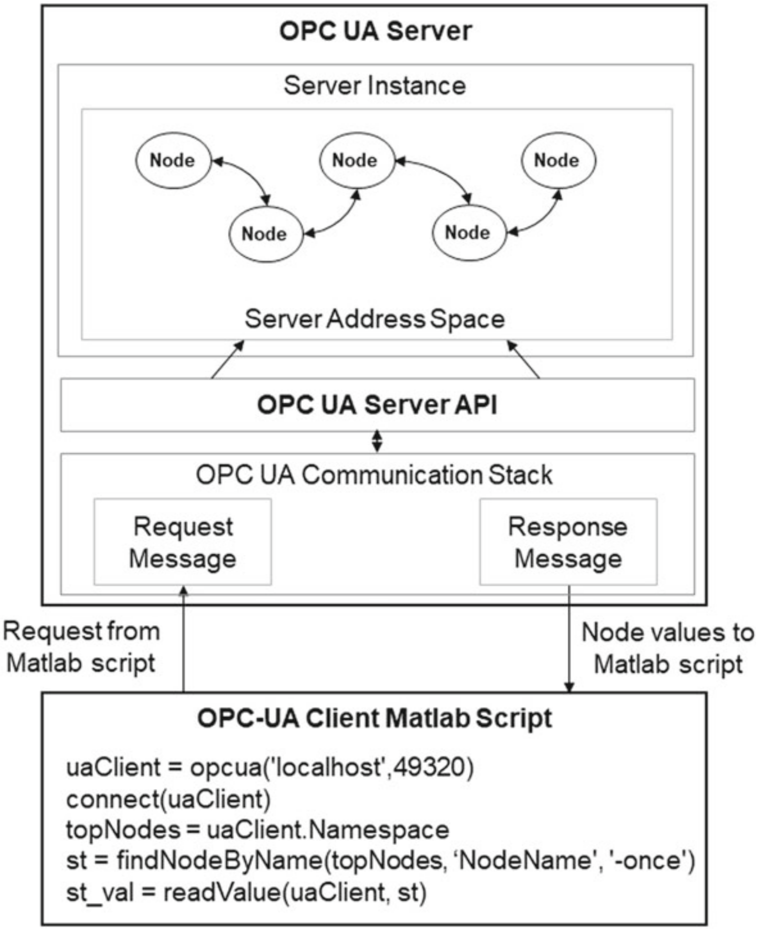


Fig. 3 OPC-UA-based KepserverEX-MATLAB communication implementation

after some data pre-processing. The function of data pre-processing is to aggregate data and make it available in a compatible form for the visualization script. Functions used for this are entirely application dependent. In this project, a smart lathe machine is considered, hence metrics like Time since Failure, Time since last maintenance and others are derived in MATLAB from the available simulated tags. Depending upon the application-specific requirements, level of computation required for this pre-processing may vary.

2.4 Intranet Deployment

Because it can be useful to have the developed application deployed on the organization's network, MATLAB provides a Web App Server package to help with this use-case [9]. This is done by generating a ctf file for the App Designer application and placing it into the app directory. Web App server can be configured to run on any of the available system ports, through which a user in the same network can access the designed application using a web browser. By default, port number 9988 is allocated, and there is also a provision to use encrypted SSL for secure access.

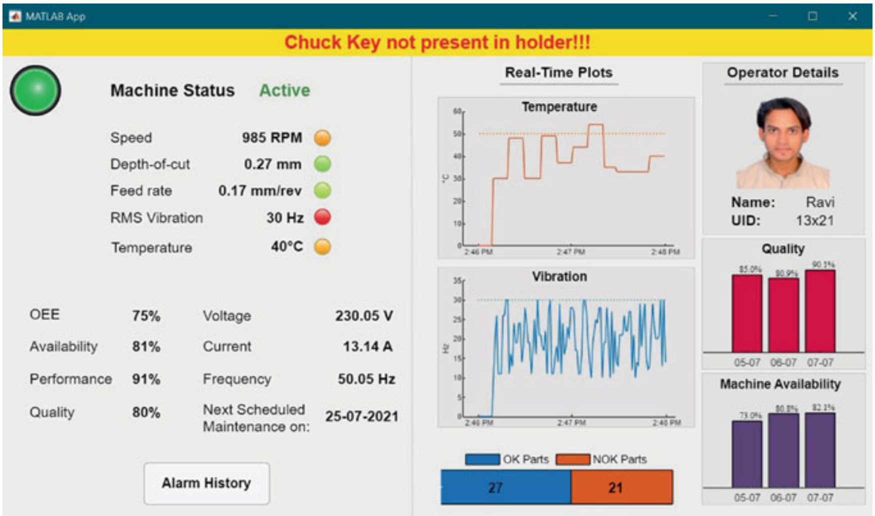
3 Results

Using MATLAB App Designer, a Graphical User Interface (GUI) is developed. In this, OPC-UA functions are called in the script to read node values at a specified rate. Based upon the received data, several types of visualizations could be executed according to the requirement of a certain user-role. Figure 4 denotes the visualized dashboards for different user roles. Line supervisor user-role is shown in Fig. 4a followed by Maintenance user-role in Fig. 4b. Figure 4c shows visualization for the electrical power aspects of the machine, whereas Fig. 4d represents the screen for Plant-Manager user-role.

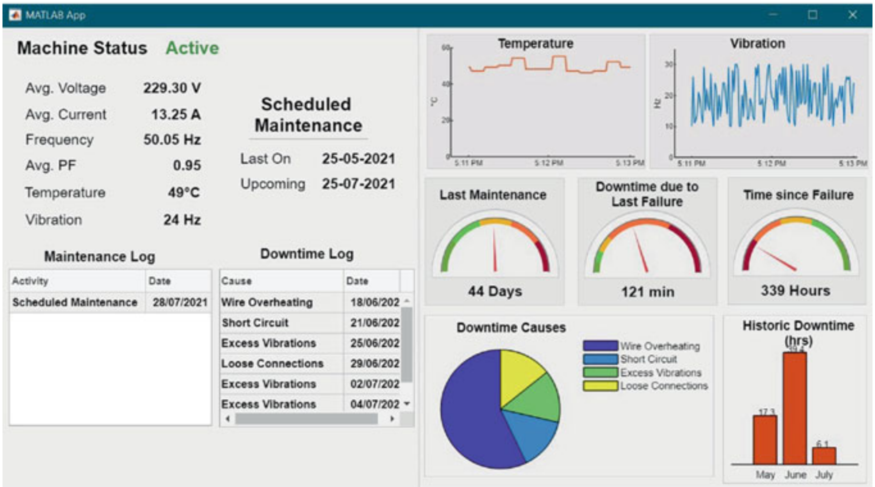
Figure 5 shows the Kepserver configuration window displaying the set of simulation tags that are developed in the application. As can be seen, three main types of simulation functions have been used along with several data types.

4 Conclusion and Future Work

A general data acquisition and visualization framework was developed which was then tailored to meet the requirements of real-time monitoring for the Smart Lathe machine. Contextualized data was presented to the user in the form of dashboards according to pre-defined user roles. Physical device presence was simulated using KepserverEX with the help of available simulation functions, and the data was sent to



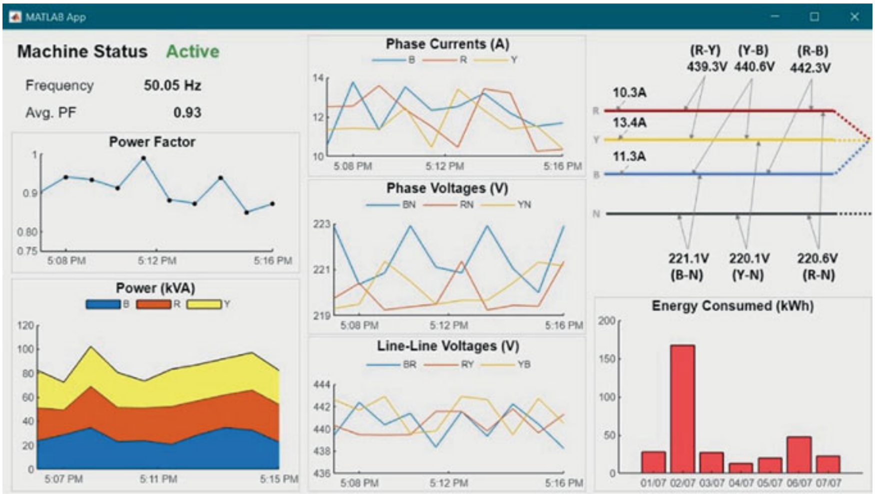
(a)



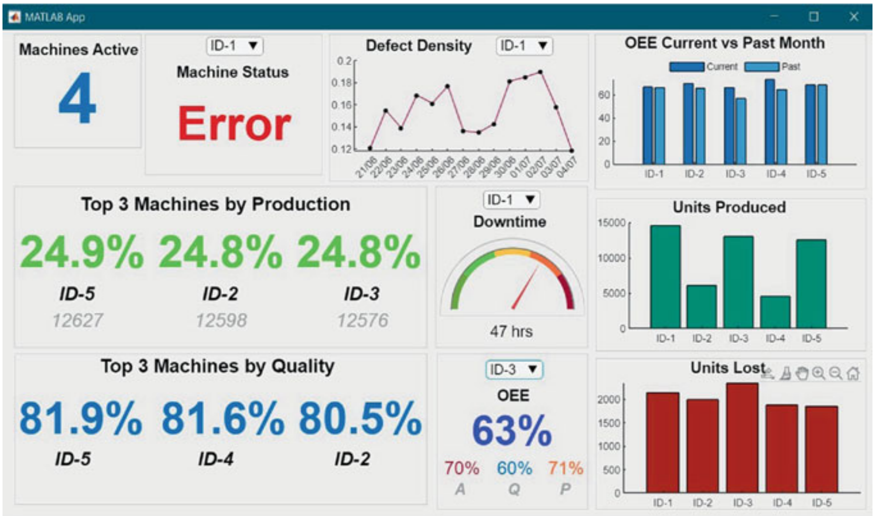
(b)

Fig. 4 Visualization of simulated data using MATLAB App Designer according to different user roles

MATLAB using OPC-UA specification. File management and data aggregation was achieved in MATLAB for displaying derived quantities and historical data. Future work includes implementation of Machine Learning algorithms on the acquired data from the physical machine to predict the Remaining Useful Life (RUL) of the tool,



(a)



(b)

Fig. 4 (continued)

and to display this computed information on a separate dashboard. Furthermore, alarms and notifications could be set up based upon the process parameters and values derived from RUL model.

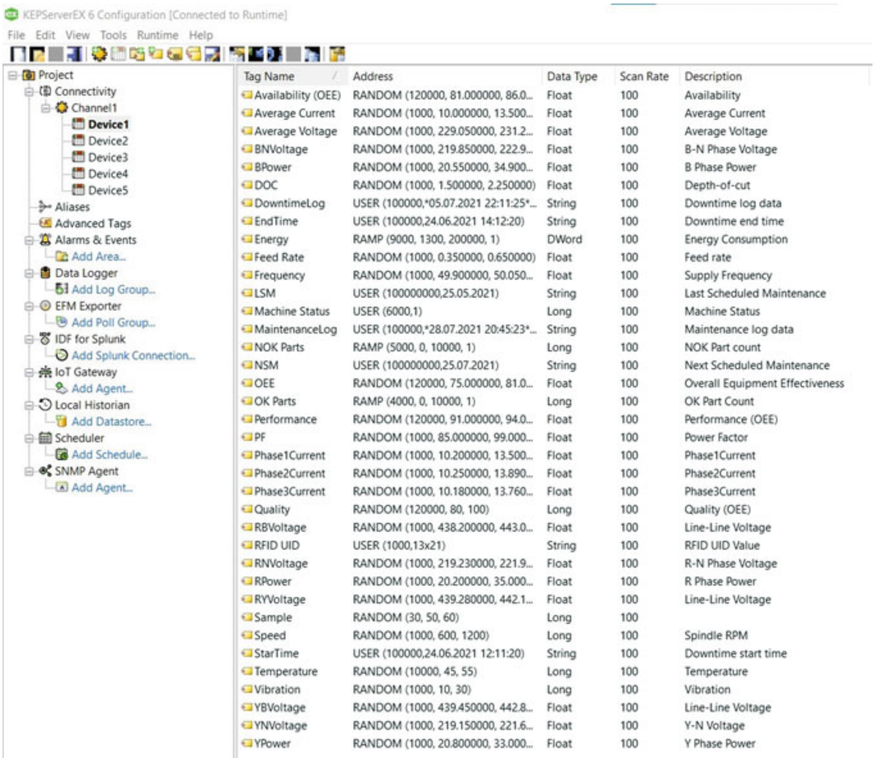


Fig. 5 KepserverEX tag list

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An Innovative Cryptosystem for Needham–Schroeder Authentication Protocols for Tertiary Industries

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1 Introduction

The binary quadratic Diophantine equations, both homogeneous and non-homogeneous, are currently addressed in many areas. Many researchers have explored non-zero integral solutions of the binary quadratic non-homogeneous equations describing hyperbolas [1–3]. In 2011, Wei [4] proposed a method for determining the integers that can be written as a sum of two integral squares for quadratic fields $Q(\sqrt{p})$ and $Q(\sqrt{-p})$ where p is a prime. Srikanth and Gopalan [5] derived a formula for finding all positive integral solutions of $Y^2 = DX^2 + N$ and also derived the solution of the equation $X^2 + 4XY + Y^2 - 2X + 2Y - 8 = 0$ by reducing it in the form $Y^2 = DX^2 + N$. Raghunandan et al. [6] used the idea of fake modulus and generalized Pell's equation for enhancing the security of RSA. Applying generalized Pell's equation in Crypto algorithms creates a big challenge in the deduction of private key. Sean Hallgren [7] provided polynomial-time quantum algorithms based on Pell's equation. Some other studies on Pell's equation in various fields can be seen in [8–13].

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One of the main communication protocols designed for employing robustness across the entire insecure network is the new version of Needham–Schroeder (N-S) protocol. Their conventions fulfill various properties, including common identification of the members, key authentication, and the construction of a common key. N-S is a shared-key authentication system that generates and distributes a shared key for symmetrically encrypted communication. The Needham–Schroeder Symmetric Key Protocol based on a symmetric encryption algorithm aims to establish a session key between two parties on a network, typically to protect further communication whereas Needham–Schroeder Public-Key Protocol based on public-key cryptography is intended to provide mutual authentication between two parties communicating on a network, but in its proposed form is insecure. The various developments on N-S protocol are seen in [14–18].

In this paper, the improved versions of N-S protocol based on the special case of binary quadratic Diophantine equation $x^2 - Dy^2 = N$ where D is a non-zero positive non-square integer and N is a perfect square which has various industrial applications are analyzed.

2 Communication Authentication Protocols

In this section, two improved versions of N-S protocols based on the equation $x^2 - Dy^2 = N$ are discussed. It is known that the only solutions of $x^2 - Dy^2 = 1$ are $(\pm 1, 0)$ where D is a positive square-free integer.

Theorem 1
If D is a square-free integer, then the solutions of $x^2 - Dy^2 = 1$ form an abelian group with identity element $(1, 0)$.

Proof Let (x_1, y_1) and (x_2, y_2) be two solutions of $x^2 - Dy^2 = 1$. Then, define a composition rule as o as $\left(x_1^2 - Dy_1^2\right) o \left(x_2^2 - Dy_2^2\right) = (x_3^2 - Dy_3^2)$ where $x_3 = x_1x_2 + Dy_1y_2$ and $y_3 = x_1y_2 + y_1x_2$. Under this composition rule, the solutions form an abelian group.

Theorem 2
If D is a positive square-free integer and N is a divisor of x^2 and y^2, then the solutions of $x^2 - Dy^2 = N$ form an abelian group with identity element $(\sqrt{N}, 0)$.

Proof $x^2 - Dy^2 = N$ can be written as $\left(\frac{x}{\sqrt{N}}\right)^2 - D\left(\frac{y}{\sqrt{N}}\right)^2 = 1$. By setting $X = \frac{x}{\sqrt{N}}$ and $Y = \frac{y}{\sqrt{N}}$, X and Y satisfy the equation $X^2 - DY^2 = 1$. Thus by Theorem 1, the result holds.

Example 1
If $D = 2$ and $N = 9$, then the solution of $x^2 - 2y^2 = 9$ has a solution as $x = 9$ and $y = 6$. So the equation becomes $9^2 - 2\left(6^2\right) = 9$. So if we divide throughout by 9,

we get $9 - 2(4) = 1$, i.e., $3^2 - 2(2^2) = 1$ which shows that (3, 2) is a solution of the equation $x^2 - 2y^2 = 1$.

Example 2
The pair (7, 4) constitutes a solution for the Diophantine equation $x^2 - 3y^2 = 1$ since $7^2 - 3(4^2) = 1$. By Theorem 1, $(7,4)^2 = (7,4)o(7,4) = (97,56)$ where $97^2 - 3(56^2) = 1$. Hence, the set of solutions of $x^2 - 3y^2 = 1$ satisfies the closure property.

Corollary 1
Finding D from $x + \sqrt{D}y$ and $x - \sqrt{D}y$ without the knowledge of the Diophantine equation $x^2 - Dy^2 = N$ is a computationally costly process, where D is a positive square-free integer and N is a perfect square.

Proof The equation $x^2 - Dy^2 = N$ can be written as $\left(x - \sqrt{D}y\right)\left(x + \sqrt{D}y\right) = N$. Denote $u = x + \sqrt{D}y$ and $v = x - \sqrt{D}y$. Then the relation will become $uv = N$. From u and v, we can write $x = \frac{u+v}{2}$ and $\sqrt{D}y = \frac{u-v}{2}$. By setting $w = \left(\frac{u-v}{2}\right) = Dy^2$, we know that D is a divisor of w. But it is not a straightforward computation. To compute D, a cryptanalyst needs to perform $O(\sqrt{z})$ computations where $z = [\sqrt{D}y]$, the integral part of $\sqrt{D}y$. Once D is identified, then $y = \frac{\sqrt{w}}{D}$ will be extracted. Thus, x, y, D will be known to us through a computationally costly process.

3 Analysis

A salient feature of the Diophantine equation $x^2 - Dy^2 = 1$ has been anlyzed and brought out in this paper. It is noted that the Diophantine equation $x^2 - Dy^2 = 1$ can be written as $\frac{x^2}{y^2} = D + \frac{1}{y^2}$. Thus $\frac{x}{y} = \sqrt{D + \frac{1}{y^2}} \to \sqrt{D}$ as $y \to \infty$. Hence, the solutions of (x_i, y_i) provide increasingly good rational approximations to $\sqrt{D}$ as y_i gets large. Also, it is noteworthy that the solutions of $x^2 - Dy^2 = 1$ lie on a hyperbola ($D = 2$) and the graph of $x^2 - Dy^2 = 1$ will form a "V"-shape for large values of D ($D > 2$) as shown in Fig. 1.

Since the complexity of finding square-free number D takes approximately $O\left(\sqrt{z}\right)$wherez $= [\sqrt{D}y]$, the cryptanalysts can perform brute force and geometric methods with the known values u and v as expalained in Corollary 1. Thus, the attackers can construct three-dimensional geometry of cone shape with keeping the values of x, Dy^2, $[\sqrt{D}y]$, and (1, 0) (where x and $[\sqrt{D}y]$ are the height and the radius of the cone, respectively). Even though any attacker can extract D with a complexity varying between $O(N^{1/4})$ and $O(N^{1/2})$, it is not certain on a time-frame of factoring Diophantine equation. In reality, it is difficult to find D from the generalized Diophantine equation where N is not necessarily a perfect square.

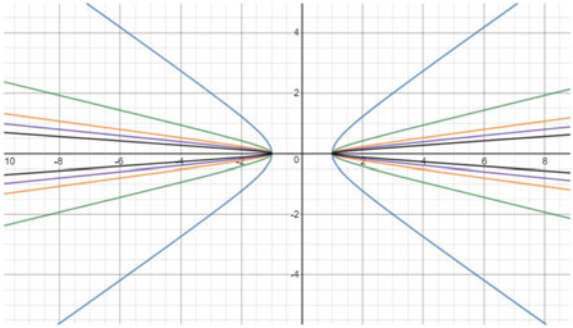

Fig. 1 Graph of $x^2 - Dy^2 = 1$ for different values of D

3.1 Protocol-1

Define $x^2 - Dy^2 = N$ where D is a positive square-free integer and N is a perfect square. Let A, S, B be the three parties involved in a communication system. Note that all communications are between A and S and A and B. But B and S do not talk directly. The authentication protocol is shown in Fig. 2. In the initial stage of communication, both A and S will have a symmetric key shared between them. Here A is a generator of the Diophantine equation $x^2 - Dy^2 = N$ and sends the encrypted values of $\{A, B, D, N\}$ to S. Using K_{as} the symmetric key generated between A and S, S independently computes $x - \sqrt{D}y$ for arbitrary values of x and y through the supplied values of D and N by A. Further A will send $x + \sqrt{D}y$ to B. Here $K_{ab} = f(D, N, timestamp)$ and K_{bs} is a symmetric key generated between B and S. At the end of this cryptosystem, A and B will come to know x and y and then the nature of the Diophantine equation (Fig. 3).

Fig. 2 First type of proposed N- S protocol

A $\rightarrow$ S: $E_{K_{as}}\{A, B, D, N\}$

S $\rightarrow$ A: $E_{K_{as}}\{D, N, B, K_{ab}, x + \sqrt{D}y, E_{K_{bs}}\{A, K_{ab}, x - \sqrt{D}\,y, N\}\}$

B $\rightarrow$ A: $E_{K_{ab}}\{x - \sqrt{D}y\}$

A $\rightarrow$ B: $E_{K_{ab}}\{x + \sqrt{D}y\}$

Fig. 3 Second type of proposed N-S protocol

A $\rightarrow$ S: $E_{K_{as}}\{A, B, N_A\}$

S $\rightarrow$ A: $E_{K_{as}}\{N, B, K_{ab}, x + \sqrt{D}y, E_{K_{bs}}\{A, K_{ab}, x - \sqrt{D}\,y, N\}\}$

A $\rightarrow$ B: $E_{K_{bs}}\{K_{ab}, A, x - \sqrt{D}y, N\}$

B $\rightarrow$ A: $E_{K_{ab}}\{x - \sqrt{D}y\}$

A $\rightarrow$ B: $E_{K_{ab}}\{x + \sqrt{D}y\}$

3.2 Protocol-2

Assume that the communication is taking place between A, B, and S. Let N_A be a random value generated by A. D is the square-free random value generated by the server S. Note that all communications are between A and S and A and B. But B and S do not talk directly. Here K_{bs} is a symmetric key generated between B and S. Then S computes $x - \sqrt{D}y$ and $x + \sqrt{D}$ y for arbitrary values of x and y and generates the session key communication $K_{ab} = f(D, N_A, timespan)$, deployed between A and B. Note that B will send $x - \sqrt{D}y$ to A and then A will come to know the equation $x^2 - Dy^2 = N$. Similarly, A will send $x + \sqrt{D}y$ to B and then B will come to know the required equation. The flow of communication protocol is shown below.

In protocol-1, S and A have more or equal priority whereas B has less priority and both members S and A will behave like a blockchain. That means blockchain nodes (S and A) can maintain: distribution of accounts, immutable records, smart contracts, trust, traceable supply chain, privacy, and security. In protocol-2, both A and B will have less priority compared to S who will be a blockchain node. Both protocols keep distinct D, N, *x,* and *y* for every transaction to avoid replay attack.

4 Applications

The proposed protocols are applied in the credit payment system which is compatible with interactive web transactions over Internet. The communication members: payers and drawers can be individuals, business or financial institutions. The working model of N-S protocol in the banking industry is shown below.

In Fig. 4, suppose client A purchases some goods from a manufacturer B. Then B will generate a voucher (in dollars) and send to A. Assume that A will not have a sufficient fund to clear the bill. In this situation, A will pass this voucher to the funding institution S which raises the fund for A. As a consequence, S will send a credit note or E-cheque to A who will transfer it to B. In this system, S and B have no mutual communication but A and B have. If either S or an attacker tries to communicate B without the knowledge of A, then the question of relay attack, mutable records, and distrust will bring into a vulnerable issue. How to overcome this challenge? A relay attack is a hacking technique related to man-in-middle and replay attacks which are all to be avoided by Corollary 1.

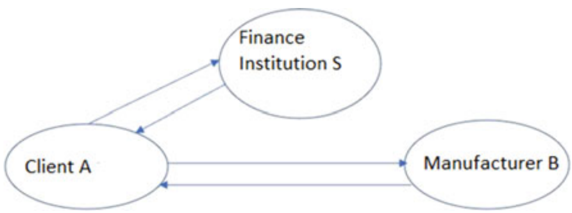

Fig. 4 Working rule for N-S protocol for purchasing goods

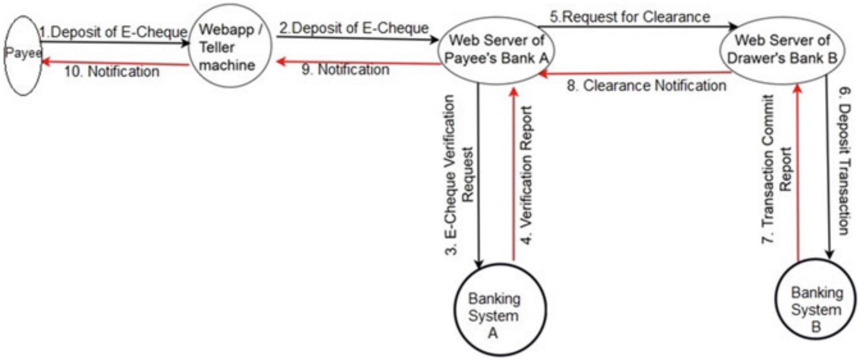

Fig. 5 Existing E-cheque transaction in banking technology

Another banking application is described here for E-cheque transactions from one bank to another. Let us have a case study: a payee (A) deposits an E-cheque issued by a drawer (B) through a web application or teller machine. In this transaction, there are 10 steps involved to complete the process as shown in Fig. 5.

As we proposed protocols 1 and 2, we could implement Crypto scheme 1: steps 3, 4, and 5 as one group of members and Crypto scheme 2: steps 5, 6, 7, and 8 as another for the purpose of authentication. Further, both web servers of banks A and B will act as blockchain nodes to invite more payees and drawers for more E-cheques in order to reduce operational complexity and improve the performance.

5 Conclusion

In the present study, the proposed versions of N-S protocols based on the binary quadratic equation have various industrial applications. Especially in the field of banking technology, we could design and implement on decentralized ledger for payments, clearance and settlement system, fundraising, tokenizing traditional securities, loans and credit system, trade finance by replacing paper heavy bills of lading process, fraud prevention, mortgage property through financial institutions, and retrieval of borrowers' documents by lenders. For all these kinds of transactions, we require a smart execution process and computational robust protocols. In due course, we are bringing out implementation results in the banking scenario and improving the existing network performance.

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Impact of Smart Incoming Inspection System on the Production, in a Medical Device Manufacturing MSME

Puneeth S. Kannaraya, G. H. Shreya, Manish Arora, and Amaresh Chakrabarti

1 Introduction

Quality-related issues and challenges are critical to be addressed during manufacturing [1]. Quality control in manufacturing plays a significant role in finding defective parts and processes and assuring quality outcome throughout the intended life cycle of the product. It is a vital part in the Quality Management System (QMS) which dictates the requirements of quality assurance as a regulation and standard [2]. Hence, to integrate the quality system, organizations need to follow the standards recommended by regulatory agencies and government bodies. The standards are so important that if not followed, it might affect the life of the consumer (e.g. medical devices, automotive parts, aerospace parts).

Quality assurance is defined in ISO 9000–2000 as "part of quality management focused on providing confidence that quality requirements are fulfilled" [3]. The term quality control refers to the activities or tools that are used to provide this assurance. Quality-related in-process inspection/verification is an essential part of quality control in manufacturing. Inspection in manufacturing includes measuring, examining, testing or gauging one or more characteristics of a product or process and comparing the results with specified requirements to determine whether the requirements are met for each characteristic [4]. To perform inspection activities, accurate measuring instruments are needed. Normally, this instrument is purchased; however, it may be necessary to design and build it in cooperation with process design [5]. Using human for 100% inspection requires considerable manpower that significantly increases costs and the time for inspection [6]. Even though the recent advancements in manufacturing systems have been characterized by precision of

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work through automation [7]. It is very difficult to automate any manufacturing system due to budget constraints, space constrains or lack of skilled labour [2].

The issues and challenges are mostly encountered in the MSMEs. The Indian MSMEs are the main contributors of the Indian economy, especially in medical devices, 65% of the indigenous manufacturers are categorized under MSME in India. There are 750–800 domestic medical device manufacturers in India, with an average investment of $2.3–2.7 million and an average turnover of $6.2–6.9 million and contribute 30% or (USD 1.1 billion) to the Indian medical devices market [8]. Even with this huge contribution the MSMEs struggle to compete with the global market. There are various reasons for the enterprises like lack of manpower, lack of resources, time, regulatory challenges, cost etc.

This research started in a focus to identify the challenges faced during the implementation of QMS for the certification of medical devices in Indian MSMEs. During understanding of the quality control activities of a local orthotic footwear manufacturer, it was found the inspection of the raw materials was not being performed. This was mainly due to the unaffordability of the state-of-the-art inspection setup. Therefore, a bespoke smart incoming inspection system was developed which uses off-the-shelf cameras and image processing techniques to capture image, analyse the defects and show the defects on the UI. The testing of the developed system for various light condition and for different colours of the raw materials was established earlier [9]. Brewer et al. [10] rightly said that reduction of waste, production cycle time, other non-value-added time or inventory is the purpose of a new technology, not the introduction of the technology itself.

The performance of the system was analysed using the six sigma DMAIC methodology. Statistical analysis of the final inspection data before and after introducing the smart incoming inspection system showed a significant change in the rejection rates. The impact on production was indicated by improvement in the FPY.

2 Literature

Quality means freedom from deficiencies and features of products which meet customer needs and thereby provide customer satisfaction [1]. Freedom from deficiencies is freedom from errors that require doing work over again (rework). Quality-related research has been an interesting topic among researchers for decades. Various researchers have worked on the rejection rates using different quality control methods. Most notable is by using six sigma methodology using DMAIC (Define-Measure-Analyse-Improve-Control) approach.

Gijo and Scaria [11] discuss the implementation of six sigma methodology in reducing rejection and rework in a honing process in an automobile part manufacturing company, where six sigma implementation in a manufacturing process for improving quality resulted in reduction of rejection and rework, thus improving the first pass yield from 88 to 100%. At one of the Indian small-scale unit, to improve rejection/rework rate in manufacturing products by pressure die casting process, quality was improved from 3.1σ to 3.7σ by reducing the rejection rate from 15.50% to 4.47% which is 71.2% improvement [12]. By making modification in the design of tool, viz., jig, the process sigma level is improved from 1.5 to 4.15, while the reworking rate in the manufacturing of track shoe was decreased to almost zero; this resulted into no delay in delivery and improved customer satisfaction [13]. To reduce the rejection rates, some jigs and fixtures were designed which in turn reduced the setup time and adjustments for a pump casing manufacturing using the DMAIC methodology [14]. Also, the smart manufacturing (referred to as Industry 4.0 also) has the major contribution on QMS, using smart factories, cyber-physical systems (CPS), Internet of Things (IoT), etc. [15].

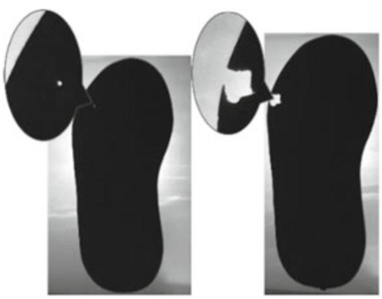
3 Methodology

To understand the quality-related issues associated with QMS, a local medical device manufacturing micro-enterprise was selected. The company produces a low-risk orthotic footwear used to cure medical conditions like calcaneal spurs, corns, heel cracks, heel pain, etc. by providing customized footwear with medial arch for flat feet, cushioned heel for heel pain, scooped insoles or offloading for ulcers, crow shoes and ankle shoes for specific foot disorders, outsole modifications for differential height, soft packed insole for corns and so on.

The footwear consists of different materials in both upper and sole parts. The bottom sole part is divided into three parts, namely, bottom sole, midsole and insole. The bottom sole is made of 10-mm-thick rubber material. The midsole is a 10 mm Ethylene–Vinyl Acetate (EVA) foam material. The insole is also a 2 mm EVA foam material. The insole is the part which directly encounters the human foot. Therefore, the raw material of the insole is considered for the inline inspection just before it gets assembled with the midsole.

To ***Define*** the problem—during the production process, the rejections are made if the defects are encountered (see Fig. 1). These rejected parts are then scrapped and considered as waste. Figure 2 shows the percentage of the insole rejections, where close to 64% are because of the rejections of insoles with defect. This is the ***Measure***

Fig. 1 Defects encountered



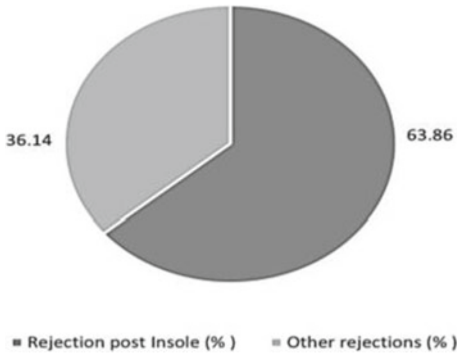


Fig. 2 % Rejections post insole cutting

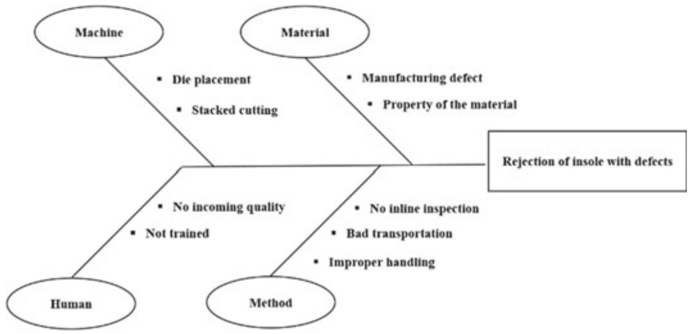


Fig. 3 Cause-and-effect diagram for the rejections of the insole

of the problem. To ***Analyse*** the problem, a cause-and-effect diagram is constructed (see Fig. 3) for the rejection of insoles with defects.

4 Experimentation

To avoid the wastage of resources like material, time and manpower, a smart incoming inspection system is proposed to introduce in the incoming stage of the raw materials to the production line (see Fig. 4). This incoming quality control stage will not only serve as a quality assurance but also a necessary inclusion to comply with the quality management system of the organization.

The design of the smart inspection system, identification of the defects and testing for various light settings were performed successfully. It has been proved the defects of at least 1 mm of size are identified within a range of 3100 lx to 3250 lx with both surface and bottom light settings [9].

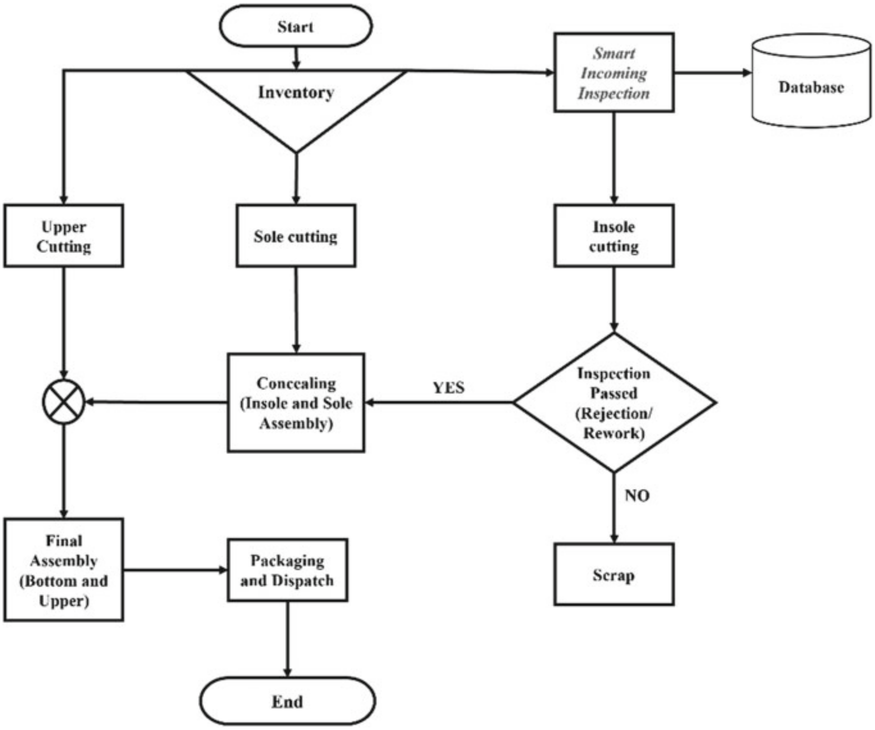


Fig. 4 Production line with the smart incoming inspection included in the insole cutting line

The raw materials were investigated using the system and labelling was done on the defects as highlighting. This helped the worker at the cutting station to notice the defective sheets. The barcode was used as the identification method which helped in registering the number of defects identified in each sheet during the smart inspection. The cutting operation was then performed by altering the stacking procedure of the sheets, which prevented the defective areas of the sheet being included in the cut-out insole pieces. The batch of cut sheets into insole was then moved to the concealing area where it was then glued with the midsole using a special adhesive. Prior to this stage is the inspection of cut insole and most of the rejection takes place here.

The program was designed to capture the defects in two forms. One is capturing the image of the defective area and storing it in local as well as cloud database and another to store the coordinate values of the defects. The latter will also have the information of the sheet, viz, dimensions, colour and unique ID (Barcode). The inspection was carried out for a batch of black and brown colour EVA sheets which was issued by the inventory for production. These sheets are examined for any defects but the data on rejection at the concealing process was collected for 4 weeks before the experiment was conducted.

To establish statistical significance for the two test groups, the experiment was based on rejecting the null hypothesis. (H0: $\sigma_1{}^2 = \sigma_2{}^2$). The hypothesis testing is by accepting alternate hypothesis (Ha: $\sigma_1{}^2 \neq \sigma_2{}^2$).

5 Results

To test the hypothesis, the data of rejection rate at the pre-concealing stage over the span of 5 weeks were collected N = 15 with $M = 1.609$ and $SD = 1.282$. Similarly, the data was collected at this stage for another 2 weeks, but for those raw materials which had undergone smart incoming inspection N = 7 with $M = 0.421$ and $SD = 0.630$. The introduction of incoming inspection enabled the production supervisor to record the defective areas in the raw material sheets. The recorded data were then statistically analysed to check for the significance and reject the null hypothesis (H_0: $\sigma_1{}^2 = \sigma_2{}^2$). An *F*-test (see Table 1) was performed to test the homogeneity of the variances of two populations with $\alpha = 0.05$ as criterion for significance F (6,14) = 4.14, $p = 0.045$. This test is a one-tailed test as to reject null hypothesis and shows the two-sample means are not equal, i.e. alternative hypothesis (Ha: $\sigma_1{}^2 \neq \sigma_2{}^2$). The independent sample *t*-test (see Table 2) was conducted to show the significance since the sample sizes were not the same, t (20) = 2.911, p = 0.0086. As the significance value α is greater than the value obtained by *t*-test, the null hypothesis can be rejected. There is enough evidence to establish the means of two samples are different and to claim the alternate hypothesis. Thus, it is evident the rejection rates after introducing incoming inspection are significant than the rejection rate without the inspection.

Figure 5 shows the rejection rates (RR_o) without inspection and rejection rates post inspection (RR_i) and the standard error mean of 0.33 and 0.23, respectively.

The ***Improve*** of the DMAIC is addressed by analysing the results after the statistical testing. The inspection of raw materials not only reduced the rejection rate but also improved the First Pass Yield (FPY) from an average of 97.65–99.52% contributing up to increase in 1.88%. As the production initiated post incoming

Table 1 F-test two-sample for variances of rejection rates with and without the smart incoming inspection

	Rejection rate (RRo)	Rejection rate (RRi)
Mean	1.609	0.421
Variance	$\sigma_1{}^2 = 1.645$	$\sigma_2{}^2 = 0.397$
Observations	15	7
df	14	6
F	4.14	
P(F < = f) one-tail	**0.045**	
F Critical one-tail	3.956	

Table 2 t-test: two-sample assuming unequal variances of rejection rates due to the unequal sample sizes

	Rejection rate (RRo)	Rejection rate (RRi)
Mean	1.609	0.421
Variance	$\sigma_1{}^2 = 1.645$	$\sigma_2{}^2 = 0.397$
Observations	15	7
df	20	
t Stat	2.9108	
P(T < = t) one-tail	0.0043	
t Critical one-tail	1.7247	
P(T < = t) two-tail	**0.0086**	
t Critical two-tail	2.0859	

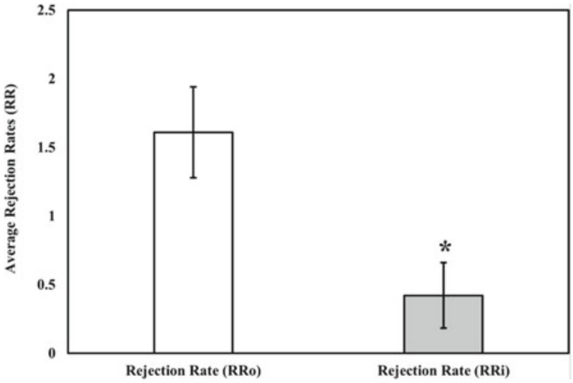


Fig. 5 Average rejection rates without and with inspection

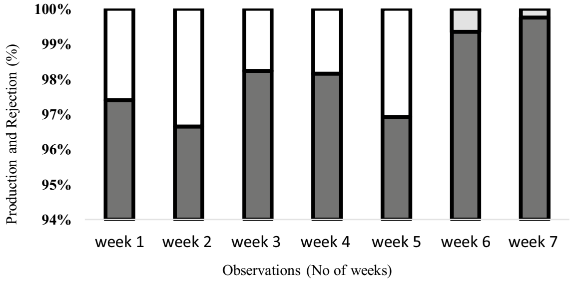


Fig. 6 Average weekly First Pass Yield (FPY) tracked over the weeks of the study. Weeks 1–5 are without smart inspection system while weeks 6 and 7 were after introduction of smart inspection system

inspection, the rejections on week 6 and week 7 are comparatively low which contributed on the overall FPY (see Fig. 6).

The ***Control*** is shown using a control chart (Fig. 7) with mean of $\mu = 1.231$ and an upper control limit (UCL) of $\mu + 3\sigma = 4.943$. The number of rejections which was closer to the UCL can be seen to be under control and equalizes to zero as the number of days go by with the inclusion of smart incoming inspection system to

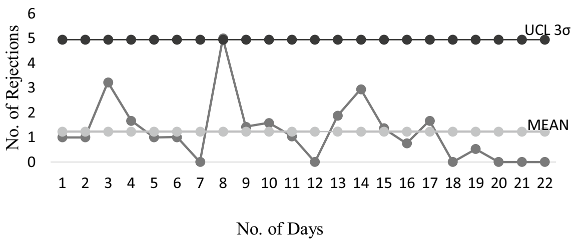


Fig. 7 Control chart for the number of rejections shown across the number of days. Number of rejections reduced from day 16 once the smart incoming inspection was introduced. (the lower control line is assumed 0, since rejections cannot go negative)

the production line. Since the mean is very close to zero the lower control line is assumed to be zero as the number of defects cannot become negative.

6 Conclusions

The quality-related challenges in a medical device manufacturing MSME were the adoption of state-of-the-art inspection system. A bespoke smart incoming inspection system was proposed and developed. It was tested for its performance in live production line of partnering MSME. The six sigma DMAIC methodology was adopted for the quality control. The incoming raw materials were tested, and inspection data was analysed using statistical process control method for the rejection rates before and after introducing incoming inspection stage and smart incoming inspection system in the production line. The analysis resulted in more than threefold decrease in rejections and improvement in FPY by 1.88%.

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What is Industry 4.0 for India?

Amaresh Chakrabarti

1 What is Industry 4.0?

According to [1], Industry 4.0 is the fourth industrial revolution. According to Wikipedia, the four industrial revolutions are as follows:

- Industry 1.0 (1760–1840), the first industrial revolution, is characterised by transition from production with human/animal power to that with machines powered by steam/water engines. It influenced iron and textile manufacturing, agriculture and mining, and strengthened the middle class [2].
- Industry 2.0 (1870–1914) was made possible with railroad networks and the telegraph that enabled faster transfer of people and ideas, and factory electrification and modern production lines that provided organised production, with high economic growth and productivity but major job losses [3].
- Industry 3.0 (late twentieth century) was marked by extensive use of computers and communication technologies in production [4], and automation of individual machines or processes.
- The original term "Industrie 4.0" originated in 2011 in Germany. Industry 4.0 is unfolding at present, to provide connected manufacturing intelligence using a combination of technologies e.g. 'Cyber-Physical-Systems', 'Internet of Things', etc. for greater autonomy in the industrial system, promising better productivity, flexibility, quality, resource utilisation, etc. [5–7].

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2 Benefits and Threats of Industry 4.0

PWC Survey on 5 core EU industry sectors [8] identified 10 key opportunities and challenges in adopting Industry 4.0:

- Industrial Internet transforms *entire organisation* and therefore should be part of the CEO's agenda.
- By 2020, European organisations will invest 140 billion Euro/year in Industrial Internet applications.
- In 5 years, more than 80% of the companies will have *digitalised* their *entire value chain.*
- The Industrial Internet increases *productivity* and *resource efficiency*; an 18% increase in 5 years.
- *Integrated analyses* and *use* of data are the key capabilities of the Industrial Internet.
- *Digitization* of the *product* and *service* portfolio is the key to sustainable corporate success.
- Digitised products and services generate 110 billion Euro/year for European organisations.
- Industrial Internet paves way for often *disruptive*, digital *business models.*
- Horizontal cooperation leads to improved customer satisfaction. This requires close cooperation among the value chain *within* the organisation as well as with the value-chain *partners.*
- Industrial Internet also holds several challenges, where industry organisations and policymakers can help. Key challenges are *high investment*, often *unclear business cases*, lack of binding *standards*, need for new *skills* and issues of *security.*

3 Key Technologies and Elements of Industry 4.0 and Their Influence on Competitiveness

According to Boston Consulting Group [9], there are nine key technologies in Industry 4.0: Big Data and Analytics, Autonomous Robots, Simulation, Horizontal and Vertical System Integration, The Industrial Internet of Things, Cybersecurity, The Cloud, Additive Manufacturing, Augmented Reality.

The key elements in Industry 4.0 technologies are as follows:

- The objects/components of the system adopting Industry 4.0 are *self-aware* (data collected about these, e.g. with sensors)
- The components are *connected* to one another and to storage devices (data exchange using, e.g. IoT devices and communication networks)
- Data collected is continuously *stored*, real-time (typically in edge, fog or cloud computing devices)
- Autonomous *analytics* are carried out on data (decisions made typically using various AI tools).

While substantial hype around Industry 4.0 technologies and their likely benefits for industry in general (as discussed in Sect. 2) exists, there is a lack of clarity as to how valuable the various specific offerings of Industry 4.0 technologies are for the various Key Performance Indicators (KPIs) of interest in the various specific sectors of the manufacturing industry. In this paper, we propose the use of an influence diagram with arrows as causal links that connect the KPIs to the I4.0 technologies as a way of representing their influences and driving empirical studies to seek greater clarity.

An example influence diagram is shown in Fig. 1, where competitiveness of an industrial system in offering a unique value proposition to its stakeholder is taken as the overall goal, which it intends to support by its value chain: value in the product on offer, value in the production, value in its supply chain and the value proposed through its business. Industry 4.0 technologies are taken as the basic influences exerted on the industrial system. The technologies are intended to influence, directly or indirectly via the four major aspects of digitalization (data collection, exchange, storage and analytics), the various values desired.

In the diagram in Fig. 1, the value offered only via production is elaborated. This value, value in production, is likely to be influenced by, among others, the quality, productivity, flexibility, safety and cost of production. These parameters are intended to be influenced, directly or indirectly via the value created by data collection, storage, exchange or analytics, by the various Industry 4.0 technologies. For instance, Internet of Things (IoT) promises to provide ubiquitous connectivity among the elements in an industrial system, thereby profoundly influencing data exchange

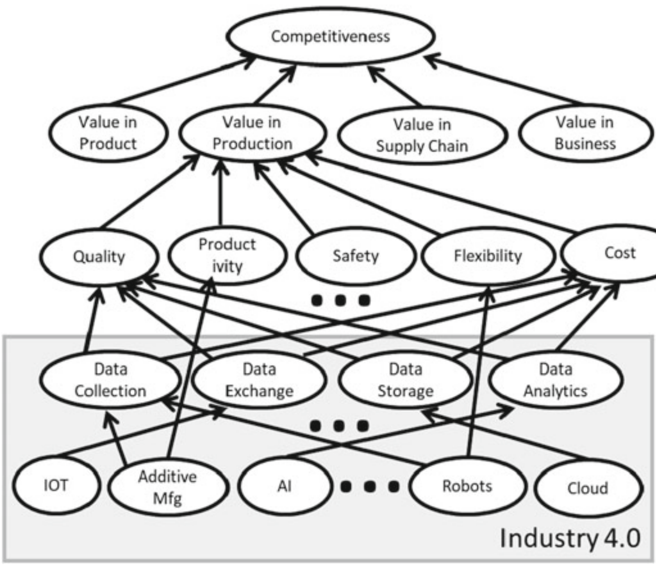

Fig. 1 Key elements of Industry 4.0 and their possible influences on key performance indicators, for various functions in and competitiveness of an enterprise

and associated downstream processes such as analytics. Additive manufacturing is intended to influence productivity, specifically for low volume production, as well as cost of production. Robots, including Automated Guided Vehicles (AGVs), are intended to provide high levels of flexibility in handling. Cloud Technology should support data storage, while Artificial Intelligence (AI) is intended primarily for data analytics. Additive manufacturing should provide greater productivity in low volume manufacturing, while also providing greater flexibility at lower cost.

In order to complete the above influence diagram, the factors of influence that are relevant for each part of the value chain (e.g., product development, supply chain, business, etc.) of the organisation or sector need to be identified and included in the diagram. The overall diagram then can be used to guide empirical studies of the organisation or sector so that those factors that play key roles in the sector can be identified. This knowledge can then be used to guide development of technologies, training, financial support, awareness and other aspects of an ecosystem for Industry 4.0.

4 Degree of Implementation of Industry 4.0 in an Entity

Assessment of the influence of introduction of Industry 4.0 technologies on an entity (e.g. enterprise, industry, industry sector or organisation) requires a measure of the degree of implementation of Industry 4.0 in the entity; without such a measure, the differential created as a result of implementation of new interventions (e.g. Industry 4.0 technologies) would remain vague, and so would be the quality of conclusions that can be drawn from empirical studies trying to understand the impact of this implementation differential on the entity.

In Appendix 1, a matrix is proposed to help assess the degree of implementation of Industry 4.0 in an entity. The columns represent the functional units of the entity: e.g. product development, production, supply chain and business; each comprises tools, activities, actors, environments and materials that are used in the functional unit, as proposed in [10].

The rows represent the four major digitalization functions that are at the core of Industry 4.0: data collection, exchange, storage and analytics. Each cell represents the intersection of the row (degree of implementation of the relevant digitalization function) and the column (the corresponding entity function). Any measure for assessing the degree of implementation of Industry 4.0 should provide an aggregation of the values in each cell, e.g. the extent to which the four functions are implemented in the elements of the four functional units of the entity. Cells in the matrix contain a qualitative description of the degree of implementation: manual, partly automated or fully automated.

The production column of the matrix in Appendix 1 is further expanded into a matrix in Appendix 2, where production function is expanded into its sub-functions, e.g. materials processing, assembly, inspection and testing, and materials handling; more functions can be added as necessary.

A manufacturing system can be at variously digitalized states, i.e. with or without data collection, with or without connectivity to enable data exchange, with or without data storage, and with or without analytics relevant for some or all components of the functions in the entity.

5 Degree of Automation in an Enterprise

It is to be noted that the organisations that may have to be evaluated and improved in terms of Industry 4.0 adoption come in all shapes and sizes: micro, small, medium and large enterprises (MSMEs and HEs), depending on the turnover and/or the number of people employed [11].

Any such organisation can be at various degrees of autonomation. The degree of automation of an organisation is an important aspect that influences adoption of Industry 4.0 and its impacts on KPIs. Therefore, a measure for assessing the degree of automation in an organisation is necessary.

A matrix, and a measure for assessing the degree of automation is proposed in Appendix 3, where the degree of automation is defined as the ratio of the sum of the degree of automation across all types of processes; if fully manual, the processes are given a value of 0 (no automation); if the processes are partially automated or only some of the processes of a given type are automated, a value of 0.5 is given; if all are automated, a value of 1 is given; the total of all of these is divided by the maximum possible value of the sum, i.e. 4. For instance, if all processes involved in material processing are 'partially automated', all processes involved in inspection and testing as well as those in assembly are 'manual', but all handling processes are 'fully automated', the overall degree of automation is given as $(0.5 + 0 + 0 + 0.5)/4 = 1/4$, which is qualitatively labelled as 'largely manual'.

6 General Issues in India with Current Models

The following are some of the hidden assumptions behind the current models of Industry 4.0 [12]:

- Availability of reliable and affordable materials.
- Availability of affordable hardware and software building blocks for the industrial sector of interest.
- Availability of affordable hardware and software technologies for the sector of interest.
- Availability of affordable and robust internet connectivity.
- Availability of common standards and protocols.
- Availability of appropriately trained workforce.
- Availability of affordable integrators.

- Availability of robust and affordable infrastructure, i.e. energy, water, space and physical connectivity.
- Availability of robust and affordable cyber-security.

However, many of these assumptions may not hold good in India and its many specific organisations, e.g. MSMEs:

- There is often a lack of availability of affordable materials with reliable properties.
- Lack of affordable hardware and software building blocks (e.g. sensors) and technologies (CAD tools).
- Lack of availability of affordable and robust internet connectivity.
- Lack of availability of common standards and protocols for Industry 4.0.
- Lack of availability of appropriately trained workforce and affordable integrators offering quality.
- Lack of availability of robust and affordable infrastructure, i.e. energy, water, space and physical connectivity; some of which are particularly expensive in India.
- Lack of availability of robust and affordable cyber-security measures in place.

These departures challenge as to whether (and which of) the Industry 4.0 technologies on offer today are suitable for (specific sectors in) India, and if not, how they need to be variously modified to suit the needs of India's specific contexts and industrial Sectors.

7 Analysis of Indian Industrial Sectors for Suitability and Readiness for Industry 4.0

As discussed in Sect. 6, given the departures in the Indian context from assumptions on the necessary conditions for adoption of current Industry 4.0 technologies, it is imperative that readiness of the various sectors for Industry 4.0 adoption be seen in the context of the costs and benefits of adopting these technologies. For assessing these (costs, benefits and readiness), it is important to see the offerings of Industry 4.0 as value propositions from the Industry 4.0 businesses (that develop and promote Industry 4.0) to the industrial sectors, and ask as to how good the value propositions are for each stakeholder involved in the proposed transaction: *Sectors* seeking Industry 4.0, *Vendors* of Industry 4.0 technologies, *Society* at large and *Ecology*). Some of the questions that are likely to be raised by these stakeholders are the following:

- *Sector:* Are stakeholders aware of the costs and benefits of the offerings? Can they afford the initial and continuing investment necessary? How valuable is the offering: is it worth affording these investments (how does return on investment change from their current status to when Industry 4.0 is adopted)? Will the sectors remain competitive if they do not adopt Industry 4.0 (i.e. how economically sustainable would the sectors be)?

- *Vendor:* Are the vendors able to provide the offering at the cost that the sectors can afford? Do they have technology and services ready for offering at that cost? What is the return on investment these offerings can make? If not, what is the cost and time for developing alternative offerings (technologies, services and so on)? What kind of return on investment are such technologies likely to make?
- *Society:* Would the society be more sustainable if Industry 4.0 offerings were adopted: e.g. what kind of job losses are expected, and will new jobs be able to recover these losses? What kind of training would be necessary for competence for such jobs, and would these be affordable for the trainees?
- *Ecology:* What are the environmental implications of the changes being offered? What are the implications on human safety and security? What are the cultural implications? Are these sustainable?

While answers to many of these questions are not clear at present, asking them in a structured and sector-specific way is necessary; this requires making some assumptions. The first assumption is that the status quo of the offering provides adequate Return on Investment (RoI) for the vendors, else these would not be on offer. The fact the Industry 4.0 offerings are not universally accepted yet leads to the assumption that the questions related to the Sectors remain largely unanswered. Including these and questions related to societal and ecological sustainability, six parameters follow:

- *Awareness:* Are the sectors aware of the costs and benefits of the offering (with respect to their status quo)? Is it worth making these investments (how does return on investment change from its current status to when Industry 4.0 is adopted)? Will the sectors remain competitive if they do not adopt Industry 4.0 (i.e. how economically sustainable will the sectors be)?
- *Availability:* Do the sectors have competence to initiate and sustain the use of the offerings? If not, is the competence externally available? Does adequate infrastructure exist to support the adoption?
- *Affordability:* Can the sectors afford the initial investment, including those for competence and infrastructure? Can they afford continuing investment necessary including those for competence and infrastructure?
- *Value:* Is the sector going to be economically more sustainable (e.g. greater Return on Investment) if Industry 4.0 offerings are adopted; or less sustainable if they are not adopted (e.g. in the extreme being wiped out of competition)?
- *Societal Sustainability:* Is the society going to be more sustainable if Industry 4.0 offerings are adopted: for instance, what kind of job losses are expected, and whether new jobs will be able to overcome these losses? What kind of training would be necessary for training for such jobs, and will these be affordable for those that need to be trained?
- *Ecological Sustainability:* What are the environmental implications of the changes being offered? What are the implications on human safety and security? What are the cultural implications? Overall, are these offerings sustainable?

When these questions are asked together, and empirical studies are performed to answer these, various combinations of answers may emerge. Possible answer scenarios, called 'situations', are presented in the table in Appendix 4. Each column asks the following question about the parameter of interest: Is the value of the parameter high or low for the sector? For instance, Is the awareness of relevant Industry 4.0 technologies for the sector high or low in the sector?

Taking answers to the questions on sustainability of the technologies as *agnostic* (as there are no clear answers on offer), 16 possible, alternative situations can be envisaged, as enlisted in the table in Appendix 4. For each situation, logical recommendations of what should be done to improve the situation are provided in the last column of the table.

As can be seen, the recommendations fall into five categories: improvement of *awareness*, *availability* (of competence or infrastructure), *affordability* (of acquiring competence, infrastructure or technologies) and *value* of these technologies (costs and benefits, RoI, etc.) for the sector.

8 Implications for Awareness and Training

While actual implementations of the empirical studies that are recommended to be carried out can only be adjudged after the studies have been carried out, some possible implications can be envisaged based on prior studies:

- *Awareness:* Since a major question that lacks clarity of sector-specific answers on the value, availability and affordability of the technologies, awareness programmes should carry out studies to answer these questions.
- *Availability of Competence:* Sector-specific competence needs should be identified, and affordable training programmes developed for each. Some of the specific areas of such training are training for developing affordable integrators of Industry 4.0; training for innovator-entrepreneurs for developing affordable Industry 4.0 technologies (including training in *design thinking and methodology*), training for developing workers of tomorrow, and training for developing manufacturing leaders of tomorrow.

9 Implications for Research, Innovation and Practice

In a similar spirit to that in Sect. 8, some possible implications envisaged in these areas are as follows:

- *Research & Development:* A major part of research should focus on understanding how the social, economic and environmental issues are likely to play out against each other across various types of manufacturing organisations adopting various types of Industry 4.0 technologies. Developing highly affordable and sustainable building blocks (e.g. sensors, actuators, controllers, IoT devices, etc.), technologies (e.g. CAD, PLM, ERP, MES, etc. platforms), protocols and standards for

Industry 4.0 functions is another major task. Affordable, sector-specific Industry 4.0 solutions will also be necessary. Finally, financial solutions are needed to enable organisations to afford initiate and sustain investment in such technologies.

- *Innovation:* Once sector-specific needs are identified, start-up culture should be encouraged and supported to focus on such needs. As discussed in the last section, the success of these is strongly linked to the quality of training of the innovators and the support ecosystem. Therefore, all of these components: awareness, training, research, development and innovation need to be connected with one another, with underlying connection of the stakeholders including academia, government, sectors, vendors (that includes innovators), as well as stakeholders representing society and ecology.

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In order to support some of these activities, e.g. spreading general awareness on Industry 4.0, demonstrating a smart factory platform, exploring new building blocks and technologies, and supporting start-ups for Industry 4.0, esp. for MSMEs, SAMARTH (Smart Advanced Manufacturing and Rapid Transformation Hub) Udyog Bharat 4.0 Program initiated by the Department of Heavy Industries, Government of India [13], has funded development of four Common Engineering Facility Centres in India: at Indian Institute of Science, Bangalore, Central Manufacturing Technology Institute, Bangalore, Centre for Industry 4.0, Kirloskar Pune, and at Indian Institute of Technology, Delhi.

The Smart Factory at IISc, called I4.0India@IISc (pronounced 'I for India at IISc'), is an expanded version of India's first Smart Factory R&D platform initiated in 2014 at the Centre for Product Design and Manufacturing (CPDM at IISc, with seed funding from Boeing USA. I4.0India@IISc has developed two contiguous but contrasting factory platforms: one champions the idea of connected industrial automation; the other the idea of human empowerment. The first uses the latest tools, e.g. metal additive manufacturing, laser routing, 5 axis CNC, etc. to be operated by robots and cobots, with material handled by Automated Guided Vehicles (AGVs). The second houses legacy machines, conventional cranes and human operators. The actors, tools, materials, processes and environment in each are digitally connected, with analytics performed on the data collected. The platforms can be combined to create intermediate platforms, so that performances of each can be assessed on key performance indicators such as productivity and quality.

11 Summary and Conclusions

The key contribution of this paper is the proposal of a framework for analysing the *value* and *readiness* of an industrial sector or an organisation for adopting Industry 4.0 technologies. Further, approaches have been proposed for helping *assess the degree of automation* involved in an organisation and its *degree of implementation* of Industry 4.0 technologies. Based on an analysis of the critical questions to be asked in determining the need and suitability of an organisation/sector for adopting Industry 4.0 technologies, *six key factors* to be investigated have been identified to determine the value of Industry 4.0 for the organisation and its readiness to adopt these technologies. These factors can be used for driving empirical studies of organisations or sectors in order to identify the main areas of value, and the specific areas of support needed to empower them to adopt Industry 4.0 to tap into this value. The factors are *awareness, availability, affordability, value, social sustainability and ecological sustainability*. The main conclusions are the following:

- A detailed study is needed to assess the value for and readiness of industrial sectors of Industry 4.0 technologies, and the areas of support they need.
- Based on this, appropriate support for awareness, training, R&D, innovation, etc. need to be targeted.
- Training must include those for innovators, and those for integrators of Industry 4.0 technologies.
- R&D and start-up support for developing affordable, sustainable Industry 4.0 building blocks, technologies and solutions targeted to serving specific needs of specific sectors are needed.
- Financial solutions (e.g. policies) to help sectors attain and sustain investments needed are necessary.
- All of these components should be connected via an appropriate ecosystem to support all the functions.

Appendix

Appendix 1 Enterprise Level Industry 4.0: Degree of Implementation of Industry 4.0 (Partly Auto: Partly Autonomous; Fully Auto: Fully Autonomous)

	Product development units or enterprises	Production units or enterprises	Supply chain units or enterprises	Business units or enterprises	Degree of implementation of enterprise 4.0
	Part/activity /tool/actor/env	Part/activity /tool/actor/env	Part/activity /tool/actor/env	Part/activity /tool/actor/env	
Data collection	Manual/partly auto/fully auto	Manual/partly auto/fully auto	Manual/partly auto/fully auto	Manual/partly auto/fully auto	When data from for parts, activities, etc. from processes in all four types of functional units is autonomously collected: data collection is fully autonomous
Data exchange	Manual/partly auto/fully auto	Manual/partly auto/fully auto	Manual/partly auto/fully auto	Manual/partly auto/fully auto	When data for all activities, parts, etc. from processes in all four types of functional units is autonomously exchanged: data exchange is fully autonomous
Data storage	Manual/partly auto/fully auto	Manual/partly auto/fully auto	Manual/partly auto/fully auto	Manual/partly auto/fully auto	When data for all activities, parts, etc. from processes in all four types of functional units is autonomously stored: data storage is fully autonomous
Data analytics	Manual/partly auto/fully auto	Manual/partly auto/fully auto	Manual/partly auto/fully auto	Manual/partly auto/fully auto	When data relevant for all parts, activities etc. of processes in all four types of functional units is autonomously analysed: data analytics is fully autonomous

Appendix 2 Manufacturing Level Industry 4.0 (Partly Auto: Partly Autonomous; Fully Auto: Fully Autonomous)

	Materials processing	Inspection and testing	Materials handling	Assembly	Degree of implementation of industry 4.0
	Part/activity /tool/actor/env	Part/activity /tool/actor/env	Part/activity /tool/actor/env	Part/activity /tool/actor/env	
Data collection	Manual/partly auto/fully auto	Manual/partly auto/fully auto	Manual/partly auto/fully auto	Manual/partly auto/fully auto	When data for all parts, activities, etc. in processes from all four types of production functions is autonomously collected: data collection is fully autonomous
Data exchange	Manual/partly auto/fully auto	Manual/partly auto/fully auto	Manual/partly auto/fully auto	Manual/partly auto/fully auto	When data for all parts, activities etc. in processes from all four types of production functions is autonomously exchanged: data exchanged is fully autonomous
Data storage	Manual/partly auto/fully auto	Manual/partly auto/fully auto	Manual/partly auto/fully auto	Manual/partly auto/fully auto	When data for all parts, activities, etc. in processes from all four types of production functions is autonomously stored: data storage is fully autonomous

(continued)

(continued)

	Materials processing	Inspection and testing	Materials handling	Assembly	Degree of implementation of industry 4.0
	Part/activity /tool/actor/env	Part/activity /tool/actor/env	Part/activity /tool/actor/env	Part/activity /tool/actor/env	
Data analytics	Manual/partly auto/fully auto	Manual/partly auto/fully auto	Manual/partly auto/fully auto	Manual/partly auto/fully auto	When data relevant for all parts, activities, etc. in processes from all four types of production functions is autonomously analysed: data analytics is fully autonomous

Appendix 3 Automation Matrix and Assessment of Degree of Automation of a Manufacturing System

Situation no	Materials processing	Inspection and testing	Materials handling	Assembly	Assessment of degree of automation
1	Manual	Manual	Manual	Manual	Fully manual (0/4)
2	Partly auto	Manual	Manual	Manual	Mostly manual (0.5/4)
3	Fully auto	Manual	Manual	Manual	Largely manual (1/4)
4	Manual	Partly auto	Manual	Manual	Mostly manual (0.5/4)
5	Partly auto	Partly auto	Manual	Manual	Largely manual (1/4)
6	Fully auto	Partly auto	Manual	Manual	Mainly manual (1.5/4)
7	Manual	Fully auto	Manual	Manual	Mainly manual (1.5/4)
8	Partly auto	Fully auto	Manual	Manual	Mainly manual (1.5/4)

(continued)

(continued)

Situation no	Materials processing	Inspection and testing	Materials handling	Assembly	Assessment of degree of automation
9	Fully auto	Fully auto	Manual	Manual	Partly manual/automated (2/4)
– - – -	– - – -	– - – -	– - – -	– - – -	– - – -
76	Fully auto	Fully auto	Partly auto	Manual	Largely automated (2.5/4)
77	Fully auto	Fully auto	Partly auto	Partly auto	Mainly automated (3/4)
78	Fully auto	Fully auto	Partly auto	Fully auto	Mostly automated (3.5/4)
79	Fully auto	Fully auto	Fully auto	Manual	Mainly automated (3/4)
80	Fully auto	Fully auto	Fully auto	Partly auto	Mostly automated (3.5/4)
81	Fully auto	Fully auto	Fully auto	Fully auto	Fully automated (4/4)

Appendix 4 Alternative Situations and Their Suitability for Adopting Industry 4.0 (Situ No: Situation Number; Awa: Awareness of I4.0 Offerings; Com: Availability of Competence to Adopt Industry 4.0; Aff: Affordability of I4.0 Offerings; Val: Value of I4.0 Offerings; Soc Sus: Social Sustainability of I4.0 Offerings; Eco Sus: Ecological Sustainability of I4.0 Offerings)

Situ No	Awa	Ava	Aff	Val	Soc Sus	Eco Sus	Implications
1	Low	Low	Low	Low	Agnostic	Agnostic	Develop offerings with higher **value** for the sector and follow Situation 2
2	Low	Low	Low	High	Agnostic	Agnostic	Develop offerings that are more **affordable**, and/or solutions to support the sector financially to adopt the offerings, and follow Situation 4
3	Low	Low	High	Low	Agnostic	Agnostic	Develop offerings with higher **value** for the sector and follow Situation 4

(continued)

(continued)

Situ No	Awa	Ava	Aff	Val	Soc Sus	Eco Sus	Implications
4	Low	Low	High	High	Agnostic	Agnostic	Develop appropriate **infrastructure** or support for **training** for competence or and then follow Situation 8
5	Low	High	Low	Low	Agnostic	Agnostic	Develop **awareness** to prevent the sector from adopting the offerings, even though they have the competence to adopt these
6	Low	High	Low	High	Agnostic	Agnostic	Make offerings more **affordable**, and/or solutions for greater financial affordability for the sector and follow Situation 8
7	Low	High	High	Low	Agnostic	Agnostic	Develop **awareness** to prevent the sector from adopting the offerings, even though they could afford and adopt these
8	Low	High	High	High	Agnostic	Agnostic	Develop **awareness** so that the sector adopts the offerings
9	*High*	*Low*	*Low*	*Low*	*Agnostic*	*Agnostic*	The sector will not adopt the offerings
10	High	Low	Low	High	Agnostic	Agnostic	Make offerings more **affordable**, and/or solutions for greater financial affordability for the sector and follow Situation 12
11	High	Low	High	Low	Agnostic	Agnostic	Develop offerings with higher **value** for the sector, and then follow Situation 12
12	High	Low	High	High	Agnostic	Agnostic	Develop appropriate **infrastructure** or support for **training** for developing competence for immediate adoption
13	*High*	*High*	*Low*	*Low*	*Agnostic*	*Agnostic*	*The sector will not adopt the offerings*
14	High	High	Low	high	Agnostic	Agnostic	Make offerings more **affordable**, and/or solutions to support the sector financially to adopt the offerings
15	*High*	*High*	*High*	*Low*	*Agnostic*	*Agnostic*	*The sector will not adopt the offerings*
16	*High*	*High*	*High*	*High*	*Agnostic*	*Agnostic*	*The sector will immediately adopt (or has already adopted) the offerings*

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Materials Processing and Joining

Machining Characteristics Study of Ti-Al_2O_3 (20 Vol.% of Ti Added as Alumina Fiber into Titanium Matrix) Composite Material While Undergoing WEDM Operation

Dwaipayan De, Titas Nandi, and Asish Bandyopadhyay

1 Introduction

As the world is approaching towards industry 4.0, new technologies are evolving to meet the demand of twenty-first centuries which give birth to new engineering materials. Thus, modern engineering materials like Inconel materials, metal matrix composite materials like TMC, AMC are coming to the forefront to meet the desire of today's industries especially aerospace, automobile and biomedical industries. But the biggest challenges lie in machining these types of hard materials with conventional machining processes becoming very much difficult. Thus, non-conventional machining processes are coming to the picture with the aim of ease to machine these types of hard composite materials. Thus, in this scenario, the present research work initiates with the aim of fabricating new composite material which can be easily machined by non-conventional machining process. Intensive literature reviews are executed in the present research work in order to identify the research gaps and also to structure the research objectives so as to visualize the research workflow. Hayat et al. [1] in their research article emphasize on the intensive use of TMC materials in modern industries because of its excellent intrinsic properties which makes it one of the promising metal matrix composite materials. Rajmohan et al. [2] describe in their research paper about the use of hybrid metal matrix composites which becomes very

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relevant in twenty-first century. Peng [3] in his research article highlighted about the fabrication process by reinforcement of Ti-6Al-4V matrix with coated SiC with the help of Vacuum Hot Pressing technique. Miracle [4] describes the importance and vast application of metal matrix composites in modern engineering industries through his research paper. Tjong et al. [5] put light on the recent development regarding the microstructure, mechanical properties, and fabrication process of the composite materials in their research paper. De et al. [6, 7] in their research paper describe about the development of pure sintered Titanium sample and machining of Ti material with WEDM operation by the using Box-Behnken design of RSM optimization technique and also analyze the effect of the different process parameters on the output responses. Kuhn et al. [8] and Konstantinov et al. [9] highlighted about the excellent properties of Ti-B based composite materials and also focuses about the importance of Ti-based alloys in their research paper. Garg [10] in his review article emphasizes about the significant application of composite materials in automobile industries. The importance of Titanium Matrix Composite (TMC) materials in aerospace and automobile industries, its fabrication process, excellent mechanical and physical properties, microstructural behavior are discussed by Threrujirapapong et al. [11], Odetola et al. [12], Chandran et al. [13], Wang et al. [14], Smith et al. [15], and Gunther et al. [16] in their research articles. Kumar et al. [17] in their research paper describes about the recent development of WEDM process which evolve as one of the most important non-conventional machining processes in recent times. Pujara et al. [18] and Garg et al. [19] in their research literatures mentioned about the use of different optimization techniques like Taguchi, Grey Taguchi, Response Surface Methodology (RSM), Artificial Neural Network (ANN), Genetic Algorithm (GA), etc., in order to improve and optimize the performances of the machining processes. But within the scope of the literature reviews, the present researcher failed to draw any conclusion regarding the fabrication process of Ti-Al_2O_3 composite material and study of its machining characteristics due to lack of research papers in this area. Thus, the present research work initiated with the aim of developing Ti-Al_2O_3 composite material where 20 volume percentages of Titanium added as Alumina fibers reinforced into Titanium matrix to form this Titanium matrix composite material and machining with WEDM to study its machining characteristics.

2 Experimental Procedure

In the present research work, four output responses, i.e., Surface Roughness (Ra), Material Removal Rate (MRR), Kerf Width (K_W), and Over Cut (OC) are taken into consideration for the purpose of evaluating the machining performances. These output responses are mapped with Pulse on Time, Pulse off Time, Wire Feed, and Wire Tension which are considered as the four process parameters in the present research work. WT 355 JOEMARS (TAIWAN) CNC Wire cut EDM has been selected as the WEDM setup for carrying out the experimental work. The wire electrode used in the machining operation was made from brass with a diameter of 0.25 mm. During machining, de-ionized water was circulated as the dielectric fluid around wire and with side flushing technique. Selections of these parameters in the present work are based on various factors such as reviews of experience, literature surveys, and some preliminary investigations. In the present research work, 20 volume percentage of Titanium taken as Alumina fiber reinforced into Titanium Matrix to develop Ti-Al_2O_3 composite material by sintering process in tube furnace at 1350 ° C in pure Argon–Hydrogen gas mixture (Ar-97% & H_2-3%) with a hold time of 2 hours. This newly developed Ti-Al_2O_3 material is considered as the workpiece material in the present research work. Twenty-seven experiments have been carried out as per the Design of Experiments (DOE) which is generated through the Box-Behnken designs (BBD) of RSM optimization technique using the Design Expert 11 and Minitab 16 statistical software to analyze the machining characteristics of Ti-Al_2O_3 composite material in the present research work.

3 Result and Discussion

27 experimental runs are constructed with different values of input parameters based on 4 factors 3 levels RSM: BBD design concept. According to the RSM:BBD design matrix, the experimental results of the output responses, i.e., Ra, MRR, Kerf Width, and Overcut obtained for 27 experimental runs are shown in Table 1. The effect of the different process parameters, i.e., T_{ON}, T_{OFF}, WT, and WF on the output responses for Ti-Al_2O_3 composite material are analyzed with the help of the different response surfaces and contour plots. Design Expert 11 software has been used for this analysis purpose.

With the help of Design Expert 11 statistical software, comparative study between the experimental results and theoretical data are plotted in a graphical format for each of these output responses in order to justify the experimental results in the present research work.

3.1 Effect of the Input Parameters on Surface Roughness (Ra)

See Figs. 1 and 2.

3.2 Effect of the Input Parameters on Material Removal Rate (MRR)

See Figs. 3 and 4.

Table 1 BBD design for actual factors and measured experimental results

Exp Runs	Input parameters				Output responses			
	Pulse on time (μs)	Pulse off time (μs)	Wire tension (kgf)	Wire feed (m/min)	Ra (μm)	MRR (mm^3/min)	Kerf Width (mm)	Over Cut (mm)
1	8	13	10	9	2.24	9.23	0.34	0.09
2	6	10	8	7	2.45	8.22	0.34	0.09
3	6	10	6	9	2.35	8.19	0.32	0.07
4	8	10	10	11	2.26	9.40	0.32	0.07
5	6	13	8	9	2.21	7.25	0.35	0.10
6	8	13	8	11	2.44	9.71	0.36	0.11
7	8	13	6	9	2.30	9.29	0.33	0.08
8	6	10	8	11	2.15	7.89	0.32	0.07
9	8	10	8	9	2.23	10.09	0.34	0.09
10	8	7	8	7	2.65	9.93	0.34	0.09
11	10	7	8	9	2.62	10.81	0.33	0.08
12	8	10	10	7	2.55	10.01	0.33	0.08
13	8	7	8	11	2.25	9.66	0.31	0.06
14	8	10	6	7	2.26	9.32	0.31	0.06
15	8	10	8	9	2.23	10.23	0.34	0.09
16	6	10	10	9	2.27	7.34	0.30	0.05
17	8	7	10	9	2.50	9.18	0.32	0.07
18	6	7	8	9	2.31	7.77	0.31	0.06
19	8	7	6	9	2.36	9.78	0.31	0.06
20	10	10	10	9	2.65	10.91	0.33	0.08
21	10	10	8	7	2.46	10.64	0.32	0.07
22	8	10	6	11	2.50	10.31	0.33	0.08
23	8	13	8	7	2.06	9.28	0.33	0.08
24	8	10	8	9	2.24	10.52	0.34	0.09
25	10	10	8	11	2.64	11.45	0.34	0.09
26	10	10	6	9	2.46	10.41	0.31	0.06
27	10	13	8	9	2.38	10.61	0.33	0.08

3.3 Effect of the Process Parameters on Kerf Width

See Figs. 5 and 6.

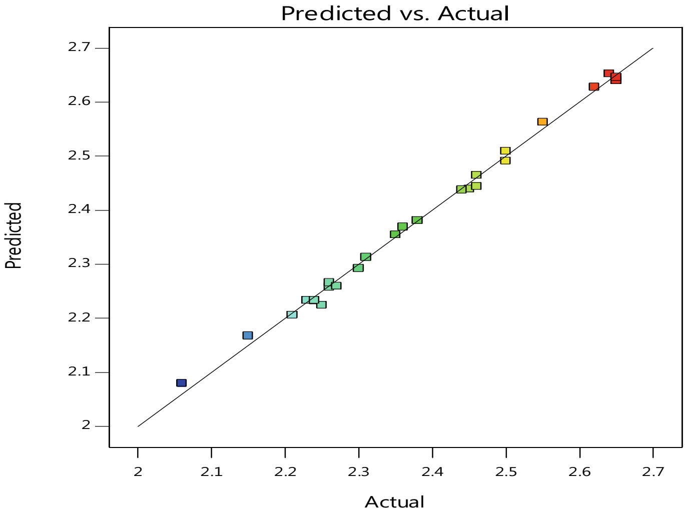

Fig. 1 Actual versus Predicted graph for Surface Roughness (Ra)

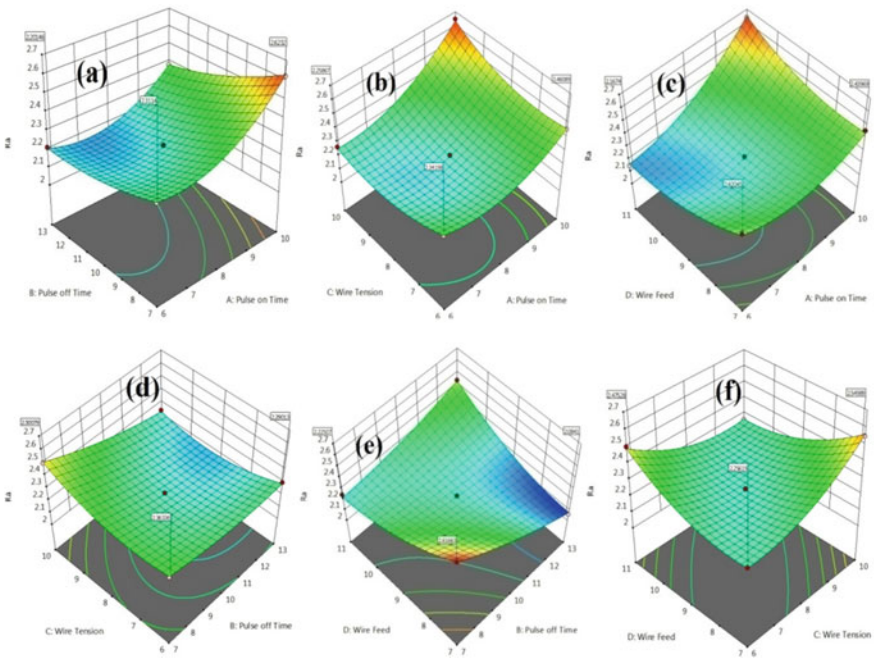

Fig. 2 Response surface and contour plots showing the interaction effects of **a** T_{ON} and T_{OFF} **b** WT and T_{ON} **c** WF and T_{ON} **d** WT and T_{OFF} **e** WF and T_{OFF} **f** WF and WT on the surface roughness (Ra) of sintered sample, while the other two parameters are at their respective center values

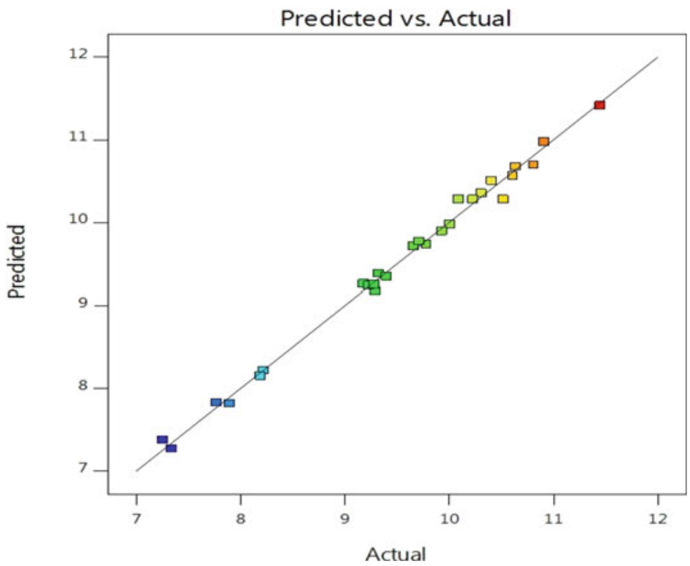

Fig. 3 Actual versus Predicted graph for Material Removal Rate (MRR)

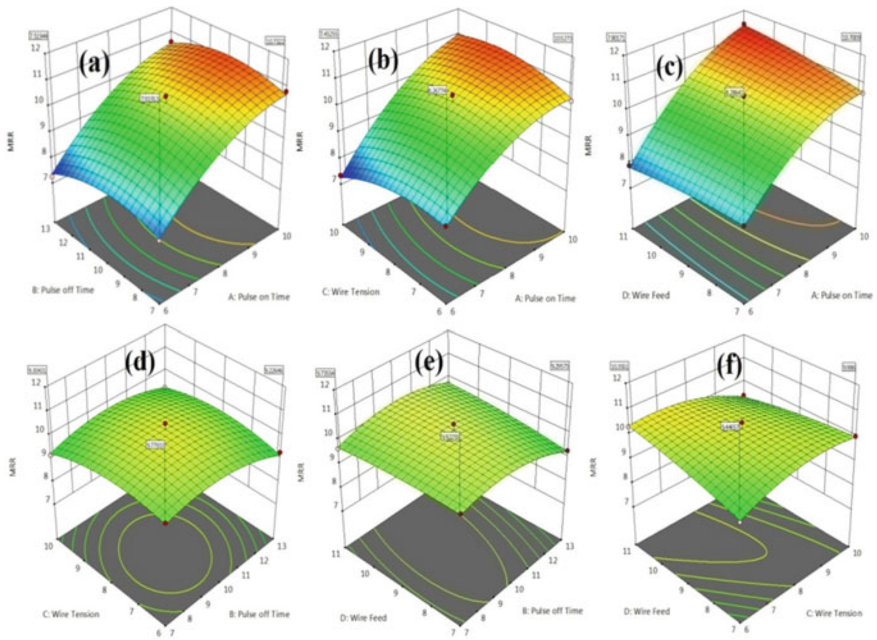

Fig. 4 Response surface and contour plots showing the interaction effects of **a** T_{ON} and T_{OFF} **b** WT and T_{ON} **c** WF and T_{ON} **d** WT and T_{OFF} **e** WF and T_{OFF} **f** WF and WT on Material Removal Rate (MRR) of sintered sample, while the other two parameters are at their respective center values

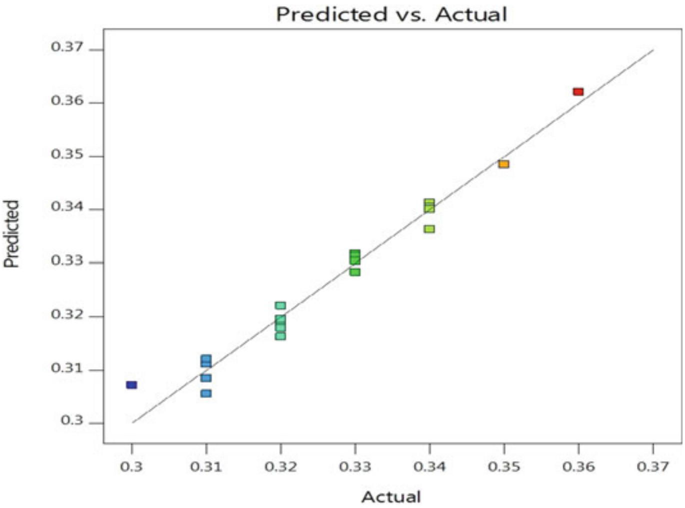

Fig. 5 Actual versus Predicted graph for Kerf Width

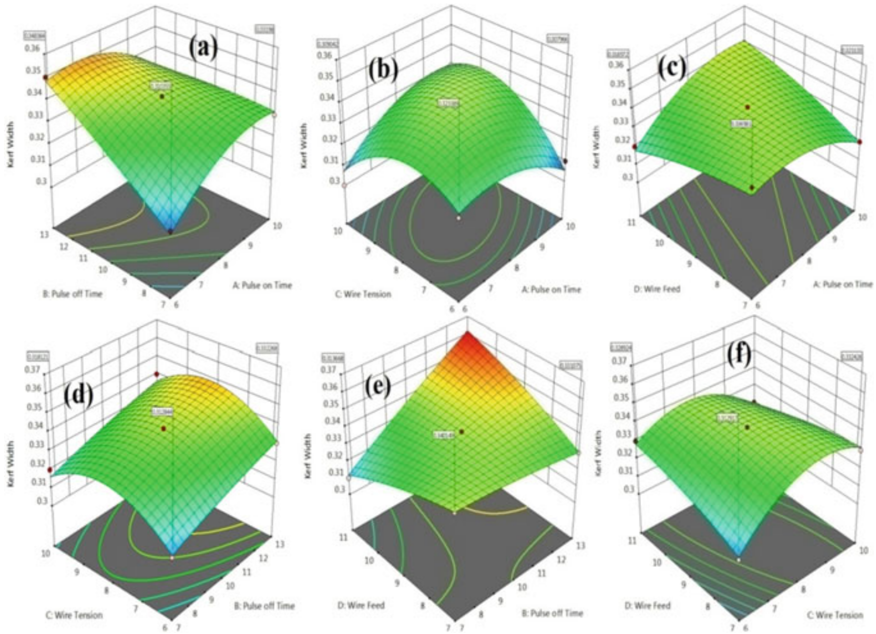

Fig. 6 Response surface and contour plots showing the interaction effects of **a** T_{ON} and T_{OFF} **b** WT and T_{ON} **c** WF and T_{ON} **d** WT and T_{OFF} **e** WF and T_{OFF} **f** WF and WT on Kerf Width of sintered sample, while the other two parameters are at their respective center values

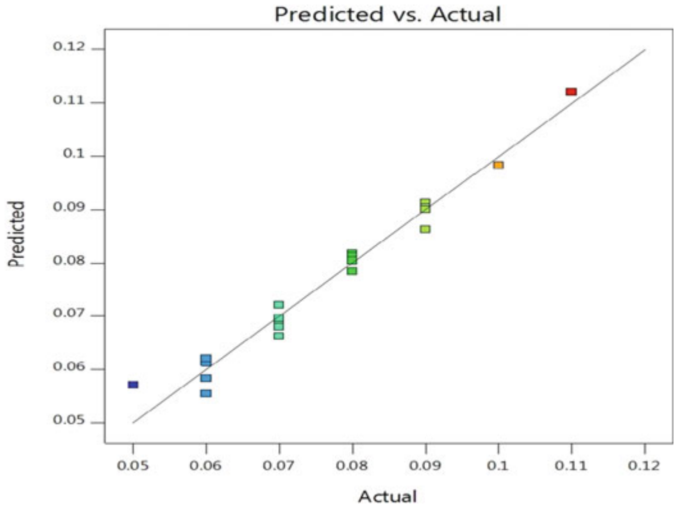

Fig. 7 Actual versus Predicted graph for Overcut

3.4 Effect of the Process Parameters on Overcut

See Figs. 7 and 8.

3.5 Experimental Observation

It has been observed that the comparative study between the experimental results and the theoretical data for Ra, MRR, Kerf Width, and Overcut as reflected in Figs. 1, 3, 5, and 7 validate the actual experimental results in the present research work. The graphical representation highlights the experimental results are scattered as points over the theoretical data line and they lie very close to each other which justify the experimental results in this context.

The 3D response surfaces and contour plots give an impression about the effect of the different process parameters on the output responses. It has been clearly observed that with the increase of Pulse on Time, Ra value increases, whereas decrease of Ra value is observed with the increase of Pulse off Time. Thus, surface texture and surface finish improve with the increase of Pulse off Time, whereas deterioration of the surfaces observed with the increase of Pulse on Time. On the other hand, MRR increases with the increase of Pulse on Time, whereas decrease of MRR observed with the increase of Pulse off Time. Thus, productivity of the process significantly increases with the increase of Pulse on Time. Thus, Pulse on Time and Pulse off Time play the most important role in terms of influencing the output responses, i.e., Ra and MRR while undergoing WEDM machining of Ti-Al_2O_3 composite material.

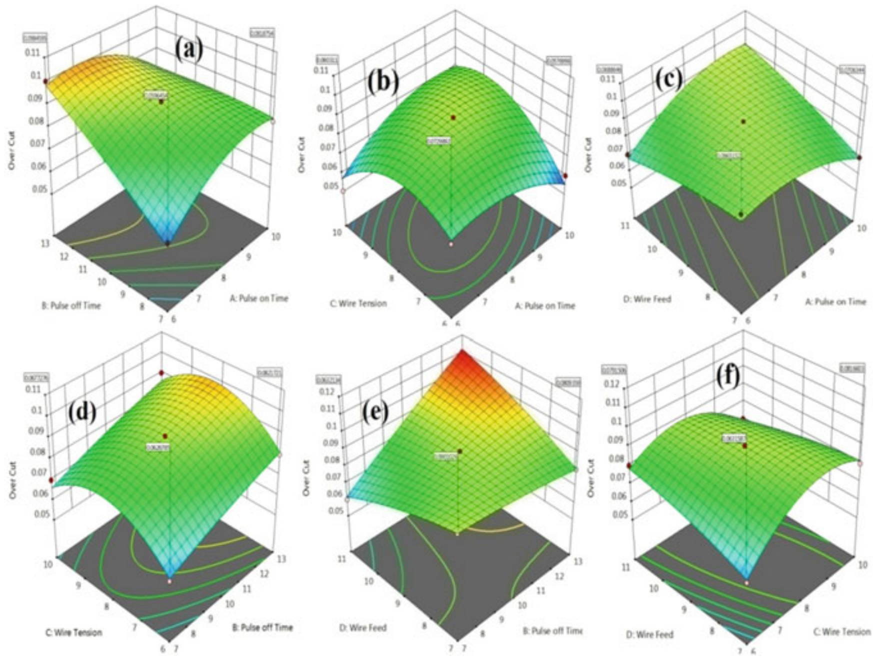

Fig. 8 Response surface and contour plots showing the interaction effects of **a** T_{ON} and T_{OFF} **b** WT and T_{ON} **c** WF and T_{ON} **d** WT and T_{OFF} **e** WF and T_{OFF} **f** WF and WT on Overcut of sintered sample, while the other two parameters are at their respective center values

4 Conclusion

Following conclusions can be projected for this type of sintered Ti-Al_2O_3 composite material while undergoing WEDM operation on the basis of experimental results and using the RSM: BBD optimization technique.

- Pulse on Time and Pulse off Time play the most important and dominant process parameters role in terms of influencing the output responses specially Ra and MRR.
- Comparative study between the actual values and the theoretical data reflected with the help of graphical presentation justify and validate the experimental results in the present research work

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Design and Development of Miniature Low-Cost Vacuum Setup for Sand Casting

Subodh B. Daronde, Abhay M. Kuthe, and Bhupesh D. Sarode

1 Introduction

Sand casting is a commonly used casting technology in manufacturing industries. It creates complex and customized parts with blends, curved surfaces, and numerous thicknesses inside the wide variety of sizes in a cost-effective way [1–3].

The existing sand casting system comprises a metal furnace, sand mold, and pattern, and casting took place at atmospheric pressure. The existing sand casting process is cheaper, but it comes with defects like surface projection, porosity, hot tearing, and unfilled cavity sections. Unfilled cavity section mainly occurs due to insufficient metal or low melting temperature of mold [4]. Porosity defects are mostly present due to pouring turbulence [5, 6]. These defects can perform as stress raisers or stress concentrators in sand casting and adversely affects the mechanical properties of the sand cast part.

There are various ways to eliminate casting defects, like adding allowances in a pattern or changing mold design. However, to eliminate porosity defects, one possible way, i.e., applying a vacuum in the sand casting process. Vacuum casting is a profoundly adaptable technology proficient in manufacturing parts with minimal defects. However, presently, vacuum is used in high-pressure die casting only, and it is costly.

In the present study, the author did sand casting under a vacuum where the liquid molten metal is drawn into the mold cavity below atmospheric pressure. This process is used when the oxide formation of metal in casting is a problem. The proposed setup in this paper for the vacuum sand casting was designed and developed in-house. The vacuum sand casting setup is acquainted with a vacuum pump connected to the vacuum chamber (heating chamber and mold placing chamber). All air and gases are drawn from the vacuum chamber and create a low-pressure before casting process.

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Melting and pouring operations were done in a vacuum atmosphere, and molten metal was directly poured into a mold cavity by bottom pouring arrangement [7]. The sufficient vacuum allows the molten metal to flow freely without creating a cold shut [8].

2 Materials and Methods

2.1 Design and Development of Low-Cost Vacuum Setup

The vacuum sand casting experimental setup used in this study was developed at Visvesvaraya National Institute of Technology (VNIT), Nagpur, Maharashtra (India). The existing Electrotherm induction furnace was modified into a vacuum induction furnace. 1HP rotary vacuum pump was used to create vacuum atmosphere inside the vacuum chamber. Sealing of the vacuum unit was done with a double-acting elastomeric O-ring having a diameter of 5 mm. The required pressure for the vacuum setup was obtained by adjusting the vacuum valve attached to the rotary vacuum pump. A Pirani gauge was used to measure the pressure inside the vacuum chamber. $P_t - R_o$ thermocouples were used to control the melting temperature of the melt.

The complete chamber is of austenitic stainless steel SS304. Based on a pressure vessel design (Eq. 1) [9], vacuum chamber is designed to hold the vacuum of 1×10^{-3} mbar.

$$t_{min} = ((C.z.a)/10)\sqrt{P/f} \tag{1}$$

where 't_{min}' is the thickness of vacuum chamber; '*a*' is a short non-linear head span.; '*b*' is the long non-circular head span; 'z' is a non-circular head factor dependent on the ratio of short non-linear head span to long non-circular head span = a/b; '*C*' is a factor depending upon the methods of attachment to the shell (0.7); '*P*' is designed pressure in kgf/cm^2, and '*f*' is allowable stress in kgf/mm^2.

The complete system is a single rigid enclosure. The vacuum chamber has three main sub-unit, i.e., melting unit, mold placing unit, and bottom pouring unit (Fig. 1).

Melting Unit. The exiting induction furnace coil was enclosed with a vacuum chamber for vacuum melting (Fig. 1b). A viewport with glass is provided on the top of the melting unit to observe the melting process. The Pt − Ro thermocouple controlled the melting temperature. A specially designed bottom pouring graphite crucible was used to charge the metal (Fig. 2c). The vacuum induction melting is used for producing alloys with melting points beyond those practical for other kinds of melting processes. There is low environmental contamination and oxidation, while undesired elements, such as hydrogen or nitrogen, can be removed from the process.

Pouring Unit. The customized stopper rod mechanism for bottom pouring is attached to the top of the melting unit. Remote control operated stopper rod arrangement is

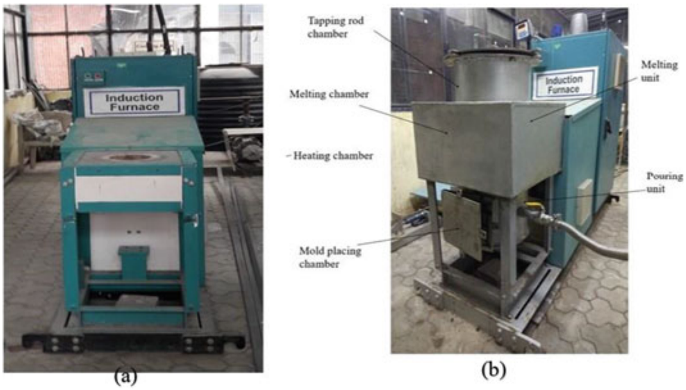


Fig. 1 Low-cost vacuum sand casting setup: **a** Exiting induction furnace; **b** modified vacuum induction furnace

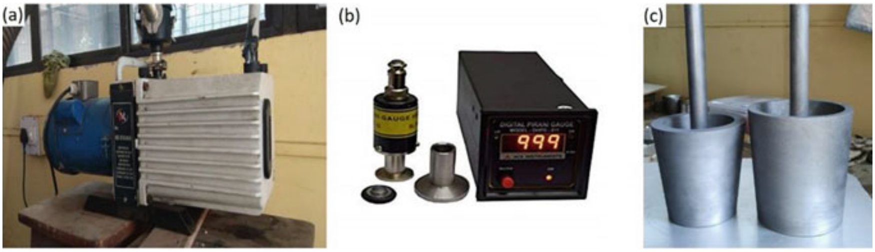


Fig. 2 Vacuum setup accessories: **a** 1HP rotary vacuum pump; **b** digital pirani gauge; **c** bottom pouring crucible

used for the operation of the stopper rod in vertical direction in order to close the bottom pouring hole of crucible during melting process and open during pouring of metal into mold.

Mold Placing Unit. The mold placing unit was attached to the bottom of the melting unit (Fig. 2b). A door was provided to the mold placing chamber for placing mold box into the pouring chamber. A laser-guided mold alignment mechanism is used for alignment between pouring basin of mold and crucible bottom hole by the LASER-guided device.

Vacuum melting setup available in the market has cost about 14–20 lack. Whereas the total costing of modified vacuum sand casting setup developed in house, including induction furnace, is cost about 5.58 lack.

2.2 Vacuum Sand Casting Process

AA6061 aluminum alloy is used as metal to understand the operation and quality of vacuum sand casting setup. Table 1 represents the metal analysis of AA6061 aluminum alloy was measured by Elvatech ProSpector 2-Handheld X-Ray Fluorescence Analyzer.

RP-assisted 3D printed pattern (Fig. 3) was used for sand casting. The shrinkage allowance of 2.5% was added to the volume of the pattern. Also, machining allowances of 1–1. 5 mm were given to the surface. The mold for sand casting consisted of silica sand (SiO_2), sodium silicate as a binder, and CO_2 as a catalyst [10].

At first, the open sand casting process was conducted at atmospheric pressure. Then, the vacuum sand casting trail was performed at a pressure of 110 mbar. Next, the vacuum was applied at the start of the melting process. Finally, the pouring operation is performed once the pressure reaches the mark pressure level [11].

2.3 Casting Quality

Porosity. The porosity of the casting specimen was evaluated by the accurate measurement of the hydrostatic weighing method using Eq. 2 [12, 13].

$$\rho_s = m1/(m1 - m2)\rho_w \tag{2}$$

where the density of the specimen 'ρ_s' in (g/cm^3), density of water 'ρ_w' at 20 °C is 0.998 g/cm^3 [14], m1 is the weight of cast specimen in air (grams), and m2 is the weight of cast specimen in water (grams). The porosity of cast specimen is

$$P = (1 - (\rho_s/\rho_{Al}))100\% \tag{3}$$

ρ_{Al} is the true density of Al6061 = 2.7 g/cm^3 [15].

Table 1 Metal analysis of AA6061 aluminum alloy

AA6061	Mg	Si	Zn	Cu	Fe	Ti	Mn	Cr	Residual	Balance
Actual Wt. %	0.45	0.6	0.04	0.02	0.27	0.015	0.043	0.0204	0.0187	Al

Fig. 3 3D printed flat tensile pattern

Mechanical Properties. The mechanical properties of the sand cast specimen were investigated using INSTRON 3300 universal testing machine (UTM) shown in Fig. 4. The tensile test was conducted at 0.1 mm/min to investigate yield strength (σ_{yt}), ultimate tensile strength (σ_{ut}), and elongation (ε).

Material Characterization. The effect of vacuum on a morphology of sand cast AA6061 aluminum alloy were investigated by scanning electron microscopy (SEM) JOEL JMS-6380A. The microstructural samples were prepared by cutting the sand cast sample into equal shapes for the composites' weight percentage and then polished on a memory bed. Finally, the polished surface was etched in 0.5 ml of HF + 1.5 ml of HNO_3 + 100 ml of H_2O.

3 Results and Discussion

3.1 Evacuation of Vacuum Chamber

The total volume of the vacuum chamber is 15820 cm^3. 1 HP rotary vacuum pump takes 7.1 min to attain an absolute pressure of 8 mbar when the full vacuum valve opens. The time required for evacuation of vacuum chamber at different valve opening is shown in Fig. 5. The actual minimum absolute pressure attains inside the vacuum chamber was 8 mbar, but due to the limiting of the sealing, maintaining absolute pressure of 8 mbar was not possible. Therefore, the actual sand casting was performed at pressure of 110 mbar.

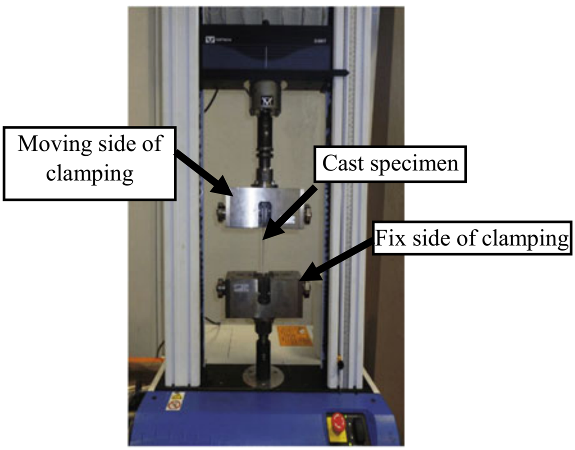
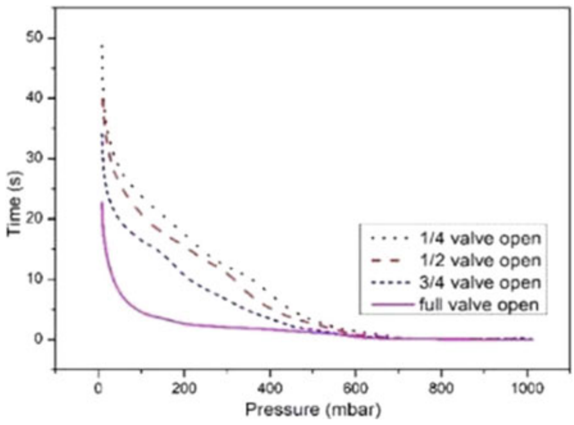


Fig. 4 Mechanical testing environment for sand cast specimen

Fig. 5 Evacuation of vacuum chamber at different valve opening



3.2 *Porosity*

Total ten AA6061 alloys were cast at atmospheric pressure by open sand casting process and 110 mbar by a vacuum sand casting process. The porosity of as-cast specimens was measured by the hydrostatic weaving method. The result of porosity for each cast specimen at different pressure is plotted in Fig. 6 and the average porosity of the sand cast specimen at different pressure is tabulated in Table 2. It was

Fig. 6 Change in porosity with respect to pressure

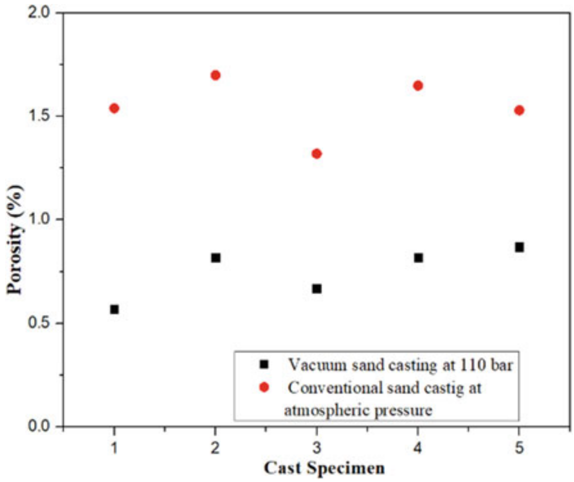


Table 2 Average porosity of sand casts specimen at different pressures

Pressure (mbar)	Average porosity (%)	STDEV
110	0.751	1.12
Atmospheric (~1000)	1.548	3.92

seen that vacuum sand casting does not eliminate total porosity, but the total volume of porosity is reduced by 80.49% when compared with open sand casting. This is because the vacuum sand casting evacuated air and gases present inside the vacuum chamber before pouring.

3.3 Mechanical Properties

The tensile tested sand cast test specimen is displayed in Fig. 7. The outcome of the tensile test is plotted in Fig. 8, and Table 3 represent the average mechanical properties of sand cast specimen at different pressure. The tensile test result of open sand casting and vacuum sand casting revealed that the ultimate tensile strength and elongation show more deviation than the yield strength for the same pressure value. It indicates that the yield strength in vacuum sand casting was not as fluctuate as ultimate tensile strength and elongation. The ultimate tensile strength in vacuum

Fig. 7 Sand cast specimen after tensile testing

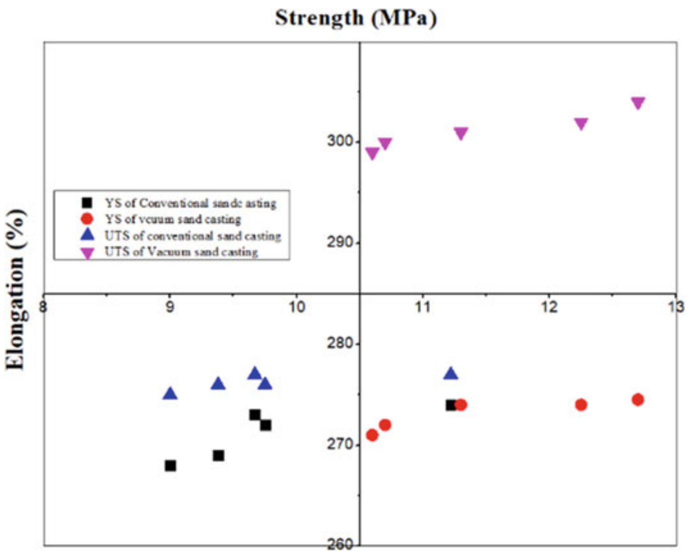


Fig. 8 Mechanical properties at different absolute pressure

Table 3 The average mechanical properties of sand casts specimens at different pressure

Pressure (mbar)	σ_{yt} (MPa)	STDEV	σ_{ut} (MPa)	STDEV	Elongation (%)	STDEV
110	273.1	1.51	301.1	0.83	11.51	1.75
Atmospheric	271.2	2.588	276.2	1.92	9.8	4.81

sand casting was increased by 11.07% compared with open sand casting. Similarly, the elongation of vacuum sand casting was improved by 18.69% than the open sand casting.

The impact of porosity on the mechanical properties of cast alloy is studied by plotting the tensile test result as a function of porosity in Fig. 9. The points shown in Fig. 9 are arranged in a linear approximation, and the equation for linear approximation is written in Eq. 3.

$$y = a + bx \tag{3}$$

where 'y' represents mechanical properties, 'a' represent strength value, 'b' represents the slope of a curve, and 'x' is the porosity of the cast specimen. This linear approximation equation is suitable for the porosity of 0.7 to 1.55%. The constraint of the straight line is shown in Table 4.

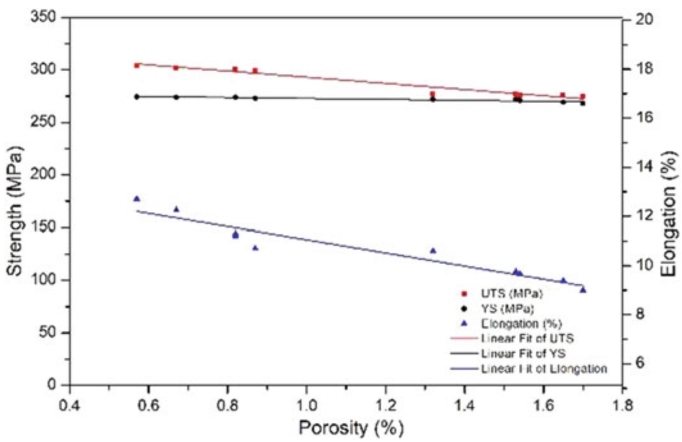


Fig. 9 Mechanical properties versus porosity function curve

Table 4 The constraints of linear approximation

Parameter	σ_{yt} (MPa)	σ_{ut} (MPa)	Elongation (%)
A	269.45	323.98	13.08
b	−2.32	−30.47	−2.09

The mechanical properties versus Porosity graph indicates that the mechanical properties of cast alloy were improved when porosity is minimized. In vacuum sand casting, the pore size and the number of pores less than the open sand casting. That can be a possibility to improve the mechanical properties of vacuum sand cast alloy.

3.4 Microstructure Characterization

The fracture surface of the cast specimen was investigated for microstructure analysis by SEM. The number of counting pores in open sand casting was 592 (Fig. 10a), whereas the number of counting pores in the vacuum sand casting is 485 (Fig. 10b). The vacuum sand casting does not eliminate the porosity in the castings but it reduces the size and number of pores on the sand cast specimen.

Large and sharp corners around pores were observed in open sand casting (Fig. 10c). Lager pores are responsible for greater stress concentration, encouraging faster fracture formation. In vacuum sand casting, small and uniformly distributed pores that initiated the slow fracture formation. Hence, vacuum sand cast specimen is difficult to break than open sand casting.

Higher magnification shows different sizes and shapes of the pores in open sand casting and vacuum sand casting (Fig. 11a and b). The different sizes and shapes of

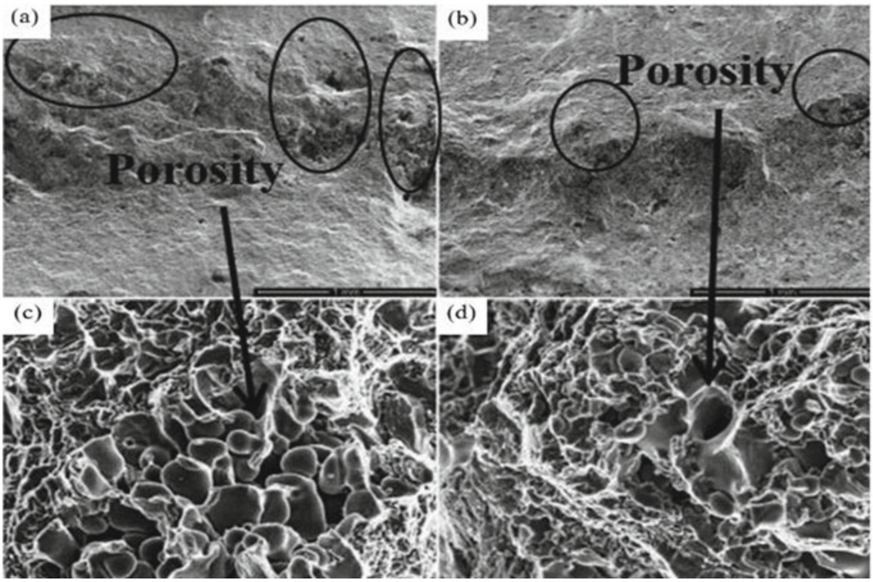


Fig. 10 Microstructure of sand cast specimen cast by: **a** & **c** open sand casting; **b** & **d** vacuum sand casting

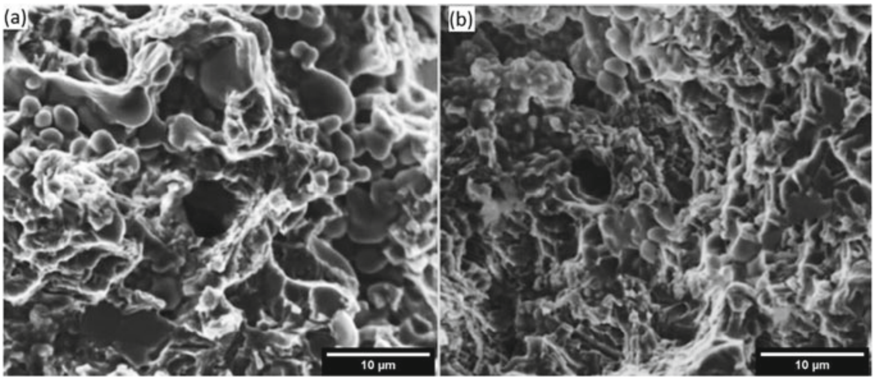


Fig. 11 Microstructure of sand cast specimen around a pore processed by **a** open sand casting process; **b** vacuum sand casting process

pores are associated with shrinkage or gas entrapment in sand castings. Shrinkage porosity has sharp corners that lead to higher stress concentrations resulting in weak sand cast specimens.

4 Conclusion

AA6061 aluminum alloy was successfully cast in a vacuum of 110 mbar. The measured porosity in open sand casting and vacuum sand casting shows that the porosity in vacuum sand casting was not completely eliminated but the amount of porosity is reduced as compare with open sand casting. The porosity of the open sand casting was 1.54%, whereas the porosity of the vacuum sand casting was 0.751. The porosity in the vacuum sand casting was reduced by 51.23%.

The tensile test result reveled that the ultimate tensile strength of open casting was 271.2 MPa, whereas the ultimate tensile strength of vacuum sand casting was 301.1 MPa. The incremental improvement of ultimate tensile strength in vacuum sand casting was 11.07%. The elongation of open sand casting was 9.8%, whereas the elongation of vacuum sand casting was 11.51%. The vacuum sand casting has 18.69% more elongation than open casting.

SEM results of open sand casting and vacuum sand casting revealed that the vacuum sand casting reduces the pores size resulting in increases the mechanical properties. The vacuum sand casting has a smaller size and uniformly distributed pores that initiated slow fracture formation.

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Technology Selection for Additive Manufacturing in Industry 4.0 Scenario Using Hybrid MCDM Approach

Anilkumar Malaga and S. Vinodh

1 Introduction

In the twenty-first century, knowledge resources increase at very high speed that do not permit conventional techniques to compete with existing manufacturing organizations. Design modifications play an important cost function, and this process begins very often and time again [1]. Additive Manufacturing (AM) refers to the technique of layer-by-layer connecting materials starting with a virtual model. A number of complicated and distinct procedures, differing for operation and materials employed, are additional manufacturing processes [2]. Additive production offers numerous significant benefits compared to traditional production processes, but probably most important is the capacity to create geometries that are highly demanding or often impossible to produce [3]. Through Smart Manufacturing (SM) technologies, the growth of digital innovation provides a new paradigm for production based on the interaction between human beings and machinery [2].

In order to strengthen AM process and enhance efficiency and quality, Industry 4.0 (I4.0) technologies have to be adopted in AM. The application of I4.0 technologies led to the industry being competitive in the global market and sustaining high performance. But industry practitioners cannot afford all technologies pertaining to I4.0 in order to implement in the industry due to high investment. For this, technologies need to be prioritized. Technology prioritization can assist industry practitioners in selecting the technologies under governing criteria pertaining to AM. Hence, this work is focused on identifying the list of I4.0 technologies that can assist and manage AM process. Then, the technologies are being prioritized using MCDM methods as a hybrid method named Fuzzy AHP-VIKOR.

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Significance of I4.0. Industry 4.0 fulfills the flexibility needed for design and production. I4.0 strives to accomplish all necessary desired functions as beneficial than that of the existing revolutions. I4.0 has a significant role in the competitiveness of the industrial economy. This revolution is excellent for automation with minimal material waste. I4.0 produces products through the latest technologies according to the customer's needs, which are the appropriate option for a personalized system on demand.

The goal of this study is to identify and rank technologies for AM in I4.0 scenario through a hybrid MCDM approach.

The remaining of this study is arranged as Sect. 2 presents the literature review, and case study is described in Sect. 3. Finally, Sect. 4 presents the conclusion of the study.

2 Literature Review

Baldassarre and Ricciardi [2] examined the usage of AM methods and demonstrated its advantages and limitations. The authors used the case study approach through which data was collected from the descriptive survey. Thus, it may be understood about the growth of I4.0, particularly the implementation of additive technology in our nation.

Chong et al. [1] explored the core information technologies through the examination of hybrid additive production. The findings showed that through the integration of digital technologies and production systems, the company could respond quickly to consumer demand, collect data, restructure information, and simulate and prototype function and design and eventually commit itself to produce the desired product.

Mehrpouya et al. [4] reviewed the latest developments and industrial applications to undertake a complete AM technology research. The authors explored AM applications in I4.0 challenges and limitations. Finally, the authors highlighted the emerging trends of AM in the fields of technology, applications, and materials that can produce new insights for future research on AM.

Butt [3] reviewed and presented the overview of interrelation among AM and I4.0. In addition, a hypothetical digital thread was presented which integrates AM and I4.0 technologies. The authors concluded that developing this digital thread for AM brings substantial benefits, enabling firms to react more efficiently to consumer needs and hasten the move to intelligent production.

Haleem et al. [5] examined the influence of AM on different fields of I4.0. The authors explored significant implications and future research guidelines for additive production. The authors concluded that AM contributes to a substantial reduction in the number of underutilized inventories in order to meet individual customer and market demands.

Wang et al. [6] examined the present Artificial Intelligence (AI) application research in AM, comprising product development, process design, manufacturing, and service operations. The authors proposed an intelligent AM framework in order to facilitate a more efficient and integrated environment for AI-enabled AM. The authors explored how AI technologies support AM products' creation and vision for the future of smart AM.

Ashima et al. [7] examined the need for SM technologies for AM operations and the benefits of IoT in AM. The authors also evaluated how integrated manufacturing technology of IoT will help industry and material suppliers. The authors concluded that IoT application of AM increased the efficiency of production, decreased waste, and satisfied the consumer criteria.

Majeed et al. [8] proposed "Big data-driven sustainable and smart additive manufacturing" framework. The framework designed by the authors was applied to selective laser melting approach of AM in a company to manufacture AlSi10Mg alloy components. The findings showed that energy usage and product quality are appropriately regulated and are beneficial for cleaner, smart sustainable manufacturing.

2.1 Research Gap

The relationship of AM with I4.0 had been explored [3]. Haleem et al. [5] explored the impact of AM in various areas of I4.0. Majeed et al. [8] developed the framework for AM in view of big data. It is noticed that the researchers focused on exploring the relationship between AM and I4.0 and on examining in concern to a specific selected technology. But the selection of technologies for AM has not been investigated. Hence, a research gap has been recognized in the identification and evaluation of I4.0 technologies for AM.

3 Case Study

The case study prioritizes I4.0 technologies to be implemented in AM using hybrid Fuzzy AHP–VIKOR approach. Fuzzy AHP and Fuzzy VIKOR approaches are multi-criteria decision-making techniques. An automobile component production company based in Tamil Nadu, India, manufactures additive automobile components suggested the integrated model used in case study. The integrated method has been utilized to determine the optimum selection of technologies. The weights of criteria have been computed using Fuzzy AHP depending on fuzzy interval arithmetic through triangular fuzzy numbers and confidence index using an interval mean method [9]. Fuzzy VIKOR is a decision-making technique for multiple considerations and a solution strategy in this work. VIKOR method was developed using various variables to get the compromise solution. The solution nearer to the ideal is called the compromise solution.

Step 1: I4.0 technologies pertaining to AM have been recognized from the literature. Identified technologies have been depicted in Table 1. In order to prioritize

Table 1 Identified list of I 4.0 technologies pertaining to AM

S. no	Technology	Research study
1	Internet of things (IoT) and Industrial IoT	Meng et al. [10]; Butt [3]; Haleem et al. [5]; Elhoone e al. [11]; Wang et al. [6]; Majeed et al. [8]; Zenisek et al. [12]
2	Big data analytics	Baldassarre and Ricciardi [2]; Meng et al. [10]; Mehrpouya et al. [4]; Butt [3]; Haleem et al. [5]; Majeed et al. [8]
3	Cyber physical systems (CPS)	Mehrpouya et al. [4]; Haleem et al. [5]; Wang et al. [6]; Majeed et al. [8]
4	Simulation (S)	Baldassarre and Ricciardi [2]; Chong et al. [1]; Mehrpouya et al. [4]; Butt [3], Zenisek et al. [12]
5	Cloud computing (CC)	Meng et al. [10]; Mehrpouya et al. [4]; Butt [3]; Elhoone e al. [11]; Majeed et al. [8]
6	Augmented and virtual reality (AR&VR)	Baldassarre and Ricciardi [2]; Butt [3]; Zenisek et al. [12]
7	Artificial intelligence (AI)	Wang et al. [6]; Majeed et al. [12]
8	Cyber-security (CS)	Baldassarre and Ricciardi [2]; Butt [3]
9	Horizontal and vertical integration (HVI)	Baldassarre and Ricciardi [2]; Butt [3]
10	Autonomous and Collaborative Robots (ACR)	Baldassarre and Ricciardi [2]; Mehrpouya et al. [4]; Butt [3]

technologies, the criteria that can govern these identified technologies have been recognized. The governing criteria are Interoperability (I), Scalability (SC), Security (SE), Networkability (N), Adaptability (AD), Compatibility (C), Flexibility (F), Accuracy (AC), Energy Competency (E), Complexity (CO), Energy consumption (EC), and Modularity (M).

3.1 *Fuzzy AHP*

The criteria weights computation using Fuzzy AHP is as follows [13].

Step 2: A pair-wise comparison matrix has been developed through the governing criteria for the selection of technology. A value is allocated to the components of the matrix depending on the relative significance of one criterion over other as per nine-point scale presented in Table 2 [14, 15].

The matrix inputs are derived from consensus views of experts with rich experience of more than 15 years in AM and I4.0. The consensus opinion of experts for criteria weights has been collected as per scale [14] and depicted in Table 3.

The linguistic inputs given by experts on a nine-point scale have been converted into fuzzy scales as presented in Table 2.

Table 2 Linguistic variables and scale of intensity using fuzzy numbers [15]

Importance in linguistic variables	Intensity of Importance (Nine-point Scale)	Triangular fuzzy numbers
Equally important	1	(1,1,1)
Intermediate	2	(1,2,3)
Moderately more	3	(2,3,4)
Intermediate	4	(3,4,5)
Strongly more	5	(4,5,6)
Intermediate	6	(5,6,7)
Very strongly more	7	(6,7,8)
Intermediate	8	(7,8,9)
Extremely more	9	(9,9,9)

Table 3 Consensus opinion of experts for criteria weights

	I	SC	SE	N	AD	C	F	AC	E	CO	EC	M
I	1	3	5	3	1	1	1	3	3	3	3	3
SC	1/3	1	1	1	1	1/3	1/3	1	1/3	3	3	1
SE	1/5	1	1	1/3	1/3	1	1/3	1/3	1/3	1/3	1/3	1/3
N	1/3	1	3	1	1	1	1/3	3	1	1	1	1
AD	1	1	3	1	1	1	1	5	3	1	3	1
C	1	3	1	1	1	1	1	3	3	3	3	1/3
F	1	3	3	3	1	1	1	5	3	3	1	3
AC	1/3	1	3	1/3	1/5	1/3	1/5	1	1/3	1/3	1/3	1/3
E	1/3	3	3	1	1/3	1/3	1/3	3	1	3	1	1
CO	1/3	1/3	3	1	1	1/3	1/3	3	1/3	1	1	1/3
EC	1/3	1/3	3	1	1/3	1/3	1	3	1	1	1	3
M	1/3	1	3	1	1	3	1/3	3	1	3	1/3	1

Step 3: The mean of the fuzzy numbers in the pair-wise matrix is calculated through the geometric mean approach [13].

$$\text{Geometric mean } r_i = (\hat{C}_{i1} \times \ldots\ldots \times \hat{C}_{ij} \ldots \hat{C}_{jn})^{(1/n)} \tag{1}$$

Step 4: Compute criteria fuzzy weight

$$w_i = (\text{lw}_i, \text{mw}_i, u\text{w}_i) = r_i \times (r_1 + r_2 + r_3 \cdots + r_n)^{-1} \tag{2}$$

where $\text{lw}_i, \text{mw}_i, u\text{w}_i$ are the lower, middle, and upper values of the fuzzy weights of ith criteria.

Table 4 Weights of the governing criteria

Criteria	Geometric mean	Fuzzy weights	De-fuzzified weight	Normalized weight
I	(1.682,2.171,2.606)	(0.116,0.178,0.261)	0.185	0.162
SC	(0.707,0.83,1)	(0.049,0.068,0.1)	0.072	0.063
SE	(0.341,0.418,0.561)	(0.024,0.034,0.056)	0.038	0.033
N	(0.891,0.998,1.122)	(0.061,0.082,0.112)	0.085	0.075
AD	(1.335,1.505,1.642)	(0.092,0.123,0.164)	0.126	0.111
C	(1.189,1.441,1.682)	(0.082,0.118,0.168)	0.123	0.108
F	(1.414,1.732,2)	(0.098,0.142,0.2)	0.147	0.129
AC	(0.348,0.439,0.595)	(0.024,0.036,0.06)	0.04	0.035
E	(0.794,0.997,1.26)	(0.055,0.082,0.126)	0.088	0.077
CO	(0.561,0.69,0.891)	(0.039,0.057,0.089)	0.062	0.054
EC	(0.749,0.909,1.122)	(0.052,0.075,0.112)	0.08	0.07
M	(0.891,1.093,1.335)	(0.061,0.09,0.134)	0.095	0.083

Step 5: De-fuzzifying the fuzzy weight into crisp value

$$W_i = ((lw_i + mw_i + uw_i)/3 \tag{3}$$

Step 6: Normalization of the weights

$$\hat{\mathrm{W}}_{ij} = W_i / \left(\sum_{i=1}^{n} W_i \right) \tag{4}$$

The weights have been computed using Eqs. (1–4) and are depicted in Table 4.

Table 4 represents the fuzzy geometric mean, fuzzy weights, de-fuzzified weights, and normalized weights of individual criteria using Eqs. 1–4. These weights will be used in further solution methodology.

3.2 *Fuzzy VIKOR Approach*

Application steps of Fuzzy VIKOR are as follows [16].

Inputs from the expert panel have been collected for technology ratings in linguistic terms as per the following scale. The linguistic scale represents the linguistic terms in trapezoidal fuzzy numbers and is depicted in Table 5.

Step 7: Aggregation and Normalization of technology ratings [17]

$$\text{Aggregation } T_{ij} = \{T_{ij1}, T_{ij2}, T_{ij3}, T_{ij4}\} \tag{5}$$

Table 5 Linguistic Scale for technology ratings [16]

Importance	Representation	Trapezoidal fuzzy numbers
Very low	VL	(0.0,0.0,0.1,0.2)
Low	L	(0.1,0.2,0.2, 0.3)
Medium low	ML	(0.2,0.3,0.4, 0.5)
Medium	M	(0.4,0.5,0.5, 0.6)
Medium high	MH	(0.5,0.6,0.7,0.8)
High	H	(0.7,0.8,0.8, 0.9)
Very High	VH	(0.8,0.9,1.0 1.0)

where $T_{ij1} = min_d\{T_{ijd1}\}$; $T_{ij2} = 1/d\sum_{d=1}^{D}\{T_{ijd2}\}$; $T_{ij3} = 1/d\sum_{d=1}^{D}\{T_{ijd3}\}$;

$$T_{ij4} = max_d\{T_{ijd4}\}$$

$$\text{Normalization}\ \mathfrak{U}_{ij} = \left\{\frac{T_{ij1}}{T^{+}_{ij4}}, \frac{T_{ij2}}{T^{+}_{ij4}}, \frac{T_{ij3}}{T^{+}_{ij4}}, \frac{T_{ij4}}{T^{+}_{ij4}}\right\} \tag{6}$$

where $T^{+}_{ij4} = max_i\{T_{ij4}\}$

The collected linguistic terms have been converted into fuzzy numbers and then aggregated and normalized using Eqs. 5 and 6.

Step 8: De-fuzzifying technology ratings in fuzzy numbers to crisp values [18]

$$\acute{P}_{ij} = \frac{1}{4}\left\{\frac{T_{ij1}}{T^{+}_{ij4}} + \frac{T_{ij2}}{T^{+}_{ij4}} + \frac{T_{ij3}}{T^{+}_{ij4}} + \frac{T_{ij4}}{T^{+}_{ij4}}\right\} \tag{7}$$

Stage 9: Evaluation of all best and worst criteria to evaluate total performance

$$\acute{P}^{*}_{i} = \max\left(\acute{P}_{ij}\right) \tag{8}$$

$$\acute{P}^{-}_{i} = \min\left(\acute{P}_{ij}\right) \tag{9}$$

The de-fuzzified crisp values of technology ratings from normalized fuzzy numbers using Eq. 7 and depicted in Table 6. The criteria have been evaluated for the best and worst cases in order to find the overall performance using Eqs. 8 and 9 and depicted in Table 6.

Stage 10: Evaluating the indices: utility ($\hat{S}_i$), regret $\left(\check{R}_i\right)$, and VIKOR ($\mathbb{Q}_i$) [19]

Table 6 De-fuzzified crisp values

Technology	I	SC	SE	N	AD	C	F	AC	E	CO	EC	M
IoT&IIoT	0.86	0.71	0.41	0.71	0.71	0.86	0.86	0.41	0.8	0.71	0.71	0.8
BDA	0.71	0.65	0.65	0.41	0.65	0.71	0.65	0.65	0.86	0.65	0.8	0.65
CPS	0.8	0.71	0.86	0.71	0.8	0.8	0.8	0.71	0.8	0.8	0.71	0.71
S	0.65	0.65	0.65	0.65	0.73	0.46	0.46	0.89	0.79	0.79	0.73	0.65
CC	0.86	0.71	0.59	0.71	0.71	0.65	0.65	0.71	0.8	0.8	0.71	0.8
AR&VR	0.8	0.65	0.71	0.8	0.8	0.71	0.8	0.8	0.86	0.8	0.71	0.71
AI	0.79	0.46	0.65	0.73	0.46	0.65	0.46	0.79	0.89	0.79	0.73	0.73
CS	0.71	0.71	0.93	0.5	0.41	0.59	0.5	0.65	0.71	0.8	0.41	0.59
HVI	0.8	0.59	0.71	0.8	0.8	0.8	0.8	0.8	0.8	0.86	0.8	0.8
ACR	0.8	0.65	0.41	0.65	0.71	0.71	0.71	0.71	0.86	0.8	0.41	0.71
Best	0.86	0.71	0.93	0.8	0.8	0.86	0.86	0.89	0.89	0.86	0.8	0.8
Worst	0.65	0.46	0.41	0.41	0.41	0.46	0.46	0.41	0.71	0.65	0.41	0.59

$$\hat{S}_i = \sum_{j=1}^{n} \{[W_j(P_i^* - P_{ij})]/[P_i^* - P_i^-]\} \tag{10}$$

$$\check{R}_i = max_i\left(W\left(P_i^* - P_i^-\right)\right)/\left(\left(P_i^* - P_i^-\right)\right) \tag{11}$$

$$\mathbb{Q}_i = \left(v\left(\hat{S}_i - \hat{S}^*\right)\right)/\left(\hat{S} - \hat{S}^*\right) + \left((1-v)\left(\check{R}_i - \check{R}^*\right)\right)/\left(\left(\check{R}^- - \check{R}^*\right)\right) \tag{12}$$

where $\hat{S}^- = \max\left(\hat{S}_i\right)$, $\hat{S}^* = \min\left(\hat{S}_i\right)$, $\check{R}^- = \max\left(\check{R}_i\right)$, $\check{R}^- = \min\left(\check{R}_i\right)$ and v is the maximum utility and $(1 - v)$ is the individual regret weight. The value of v is considered as 0.5.

Three indices have been computed using Eqs. 10–12 and depicted in Table 7.

Stage 11: Prioritizing the technologies depending on $\mathbb{Q}_i$ values. The technology with the smallest $\mathbb{Q}_i$ value is prioritized first. The derived priority order of technologies has been presented in Table 7.

3.3 Proposing Compromise Solution

In order to validate the compromise solution, the following two conditions must be fulfilled:

Condition 1: Adequate profit $\mathbb{Q}(R_2) - \mathbb{Q}(R_1) \geq DQ$

where R_2 is the second place attained in the prioritization

Table 7 Indices of Regret (Ř), Utility (Ŝ), and VIKOR index (ℚ) and Prioritization of technologies based on indices

	$\hat{S}_i$	$\check{R}_i$	$\mathbb{Q}_i$	Prioritization	$\hat{S}_i$	$\check{R}_i$	$\mathbb{Q}_i$
IoT&IIoT	0.204	0.039	0.029	I	HVI	IoT&IIoT	IoT&IIoT
BDA	0.518	0.116	0.619	II	IoT&IIoT	CPS	HVI
CPS	0.222	0.046	0.077	III	CPS	AR&VR	AR&VR
S	0.613	0.162	0.891	IV	AR&VR	HVI	CPS
CC	0.272	0.068	0.207	V	CC	CC	CC
AR&VR	0.222	0.046	0.076	VI	ACR	ACR	ACR
AI	0.496	0.129	0.654	VII	AI	BDA	BDA
CS	0.736	0.116	0.814	VIII	BDA	CS	AI
HVI	0.171	0.046	0.031	IX	S	AI	CS
ACR	0.385	0.07	0.316	X	CS	S	S

$$\mathrm{DQ} = 1/(\text{Number of technologies} - 1)$$

Condition 2: Decision-making acceptable stability. Technology ranked first should also be ranked first by the utility and/or regret measures.

If two conditions got satisfied, then the technology with least index of VIKOR be the best technology; else more than one solution will be proposed as the best solution.

In this study, Internet of Things and Industrial Internet of Things (IoT&IIoT) are ranked first, and Horizontal and Vertical Integration (HVI) ranked second as per VIKOR index.

As per condition 1, the adequate profit is $\mathbb{Q}(\text{second}) - \mathbb{Q}(\text{first}) \geq \mathrm{DQ}$

where $\mathrm{DQ} = 1/(\text{Number of technologies} - 1) = \frac{1}{10-1} = \frac{1}{9} = 0.11$

Hence, $0.031 - 0.029 = 0.002 \geq 0.11$ (Not satisfied).

Here, the condition one is not satisfied. Hence, more than one solution is proposed as the best solution.

Hence, IoT&IIoT, HVI, and AR&VR are proposed as top prioritized technologies to be used in AM.

3.4 *Implications*

This study assists industry practitioners in selecting technologies and implementing them in existing AM industry with appropriate selection of suitable technologies. The management can attain the benefit of avoiding huge investment in all technologies to implement them in Industry. Through the enhancement in manufacturing process with technologies, organization that can produce customized products with low investment can provide a facility for the consumer to monitor manufacturing process from a remote location. Real-time monitoring can be facilitated through IoT and IIoT which can be fruitful to the consumer and industry practitioners. Through enhancement in technologies, industry can be more competitive in the global manufacturing era.

Limitations and Future Scope

This study identified and analyzed technologies for AM pertaining to the automotive manufacturing industry. The other technologies may be identified based on their specific application. In the future, a model will be developed among technologies in order to identify the interrelations among them using any modeling approach.

4 Conclusion

Implementation of Industry 4.0 technologies in AM is most advantageous to the organization. I4.0 technologies can overcome difficulties in AM process and make AM into a highly technological, accurate, and quick process. For the ease of implementation of technologies in AM process, technologies are prioritized using a hybrid decision-making method. In this study, governing criteria weight had been computed using Fuzzy AHP, and technologies had been prioritized using Fuzzy VIKOR. Three indices: Utility, Regret, and VIKOR index, have been identified using hybrid method. In this, more than one compromise solution is provided for technology selection. IoT and IIoT, Horizontal and Vertical Integration, Augmented Reality, and Vertical Reality are the priority technologies selected for the implementation in AM. This study can assist industry practitioners to enhance AM organization and make the industry competitive globally.

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Synthesis of ZnO Nanostructures on Woven Kevlar Fabric and Impact of Hydrothermal Conditions on Growth of Nanorods

Ravi Shankar Rai and Vivek Bajpai

1 Introduction

Fiber-reinforced polymer composites (FRPs) are generally utilized for developing engineered constructions, particularly in aircraft industry because of their distinguished features. Over the few, years various FRPs having large span of utilizations has been created, for example, short fiber FRP, polymer/mud nano-FRP, metal matrix composites, and others [13]. All FRPs have possesses outstanding mechanical and physical properties like rigidity, chemical stability, thermal stability, and fire resistance. FRPs are generally lightweight as the material properties of the composite can be essentially improved by adding just a little volume part of fibers [9]. Kevlar {poly paraphenylene terephthalamide; PPTA}, is a broadly utilized high-strength fiber having remarkable anisotropic mechanical strength, chemical resistant, and energy retention capacity [5]. It is usually utilized in bullet armor carriers, defensive apparels, and superior high-performance FRPs for aviation and transportation. The high toughness ability of Kevlar-based FRPs gives high impact/ballistic obstruction that get from the para-benzene rings with aromatic groups between the polymer chains [1]. The interfacial region between the matrix and fibers plays an important part to modify the overall properties of FRPs. The low surface energy and chemically inert surface of Kevlar causes low interfacial bonding between the fibers and the matrix [2]. Sometimes the connection between the phases between the layers of the composites is not adequate to get the desired properties. Everything considered, reinforcement approaches to go must be gotten to upgrade the interfacial quality and furthermore the stress transfer. These features leads towards the headway of multiscale hybrid composites in which greater than one bracing media is used, considering the advancement of microscale whiskers, nanostructures like tubes, rods, and wires

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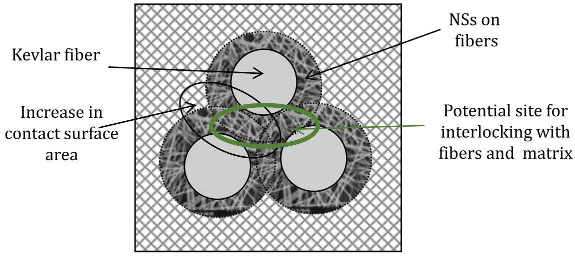


Fig. 1 Concept of increasing interfacial strength between fibers and matrix by growing ZnO

around the strands [14]. These topographies connect into the lattice, augment the surface domain for holding, and enhance stress transfer at interface region of the fiber. The type of nanostructures (NSs) with regular fiber fortifications in polymer composites has been accomplished predominantly through two distinct courses: scattering NSs altogether all through the composite network or growing NSs legitimately onto essential fortifying strands. First strategy has the simplicity of creation and compatibility with standard mechanical strategies, however, it has restriction of low loading values. However, in the second strategy, the fiber-ruled in-plane features are not altogether influenced but rather grid-dominated properties such as ILSS (interlaminar shear strength) are enhanced by about 8–30% [4]. Growing NSs onto fiber surfaces is a successful strategy to improve fiber surface region, making mechanical interlocking, and local softening at the fiber/grid interface, all of which may improve load exchange and interfacial properties explicit nanoscale impacts on the 'mass' polymer properties are likewise conceivable [4]. A pictorial representation of technique to enhance the interfacial strength between fibers and matrix by growth of ZnO NSs on fiber surface is illustrated in the Fig. 1. Chemical treatment of the fibers leads to surface modification by generating functional groups that help in the interaction with the polymer matrix. The growth of nanowires, nanorods, or nanotubes on the surface of the fibers is a promising approach to increase the interfacial strength of composites.

ZnO nanostructures have gained extensive research potential because of its inherent physical properties and demand for various electronics and photonics industries. ZnO is an appealing material on account of its wide bandgap of 3.37 eV, high exciton energy, and wurtzite structure. Scientists are regularly using ZnO NSs like nanowires, nanorods, nanoflowers and nanoflakes for a broad assortment of utilities from power gadgets to solar items to optoelectronic items [15]. Different morphologies of the ZnO on fibers are the excellent factor to achieve tailored properties of nano-FRPs. ZnO NSs developed WKF strands enhances the total contact area at the interface between fiber and polymer. Thus, the stress transfer and energy absorption of the resulting FRP increases [7]. The availability of polar groups on the strands and large fiber surface area has strong impact on the growth and bonding of ZnO NSs with Kevlar fabric. Increase in the contact surface area of ZnO NSs/WKF with polymer matrix enhances interfacial relation and improves overall properties of resulting FRP [3]. ZnO highly reacts with carboxylic compound due to strong fondness of Zn^{2+}ion with the functional groups such as –COOH and –OH. Surface treatment of WKF is an important step to enhance the affinity of ZnO NSs formation because it helps in activation of carboxylic groups and functional groups to form ionic bonds. Over the few years ago, different methods have been emerged for the development of 1D nanomaterial such as vapor–liquid–solid (VLS), template-assisted, solvothermal, and electrochemical processes. Out of all the processing techniques, a type of solvothermal called as “Hydrothermal Technique” is simple and cost-effective for fabrication of nanostructures [11]. In the field of nanomaterial chemistry, certain key factors are to be paid attention, i.e., controlled synthesis of the nanomaterial shape and size; because the materials novel properties depends on it, thus a better understanding of the emerging new synthetic processes and the growth mechanism of the nanomaterial is required [10]. In the hydrothermal process, different NSs on fiber surface can be developed by tuning the parameters such as chemical used, total duration, temperature, and molar value [11].

This paper deals with the development on ZnO NSs on surface-treated WKF using hydrothermal route and impact of hydrothermal condition such as seeding cycle and molar concentration at 8 hour of growth treatment. This work also defines the possibility and utility of making ZnO nanostructured WKF-reinforced composites with epoxy resin by vacuum bagging technique. XRD result exhibits the crystallinity and wurtzite structure of grown ZnO on WKF. FESEM was used to study the grown ZnO NSs and identify the optimum growth conditions for the nanorods. EDS analysis was used to identify the presence of grown ZnO on the surface of WKF. The potential application area of developed ZnO/WKF-reinforced polymer hybrid composite is also discussed.

2 Experimental

2.1 Materials

Unmodified WKF of grade A-200 and 220 GSM, plain weave, bidirectional fibers having 12 μm diameter and 0.32 mm thickness were used as substrate material for growth of ZnO nanostructure. Following chemical precursors such as zinc acetate dehydrate (ZAD), ethanol, sodium hydroxide (NaOH), zinc nitrate hexahydrate (ZNH), hexamethyline tetramine (HMTA), and water (distilled/de-ionized) (DIW) of analytical grade to prepare seed and growth solution were used for experiments. All the materials were used without any further processing.

2.2 Preprocessing of WKF for Growth of ZnO NSs

Small pieces of 150 mm × 150 mm WKF fabric were cut and then rinse by ethanol–acetone mixture several times to eliminate foreign elements and contaminants. Now the washed pieces were kept inside hot air oven for 15 min at a temperature of 100 °C. Now for the activation of carboxylic acid groupings available on the Kevlar surface, the samples were treated with the 10% NaOH and 10 N HCl solution for 20 min and 15 s, respectively, and then washed with deionized water several times. Finally, the samples were dried inside the oven for 1 h at a fixed temperature of 100 °C. This step removes extra metal ions and form hydrogen ion which caused development of carboxylic acids on the WKF using ion-exchange process. This will increase the potential sites for the growth of ZnO on WKF surface. The resulting samples were used for growth of ZnO NSs on the WKF.

2.3 Synthesis of ZnO Seed Solution

Seeding process is an important part of the hydrothermal synthesis for which a standard solution called as 'seed solution' is needed. To synthesized seed solution, a solution was prepared by mixing 0.30 g of ZAD in 450 ml of ethanol in a beaker at 70 °C temperature with the help of magnetic stirrer at 400 rpm till 40 min. Another solution was prepared by mixing 2.2 mM of NaOH in 100 ml of ethanol on a magnetic stirrer at 400 rpm and 70 °C temperature. Now both the solutions were mixed slowly in a large beaker and also added 250 ml of ethanol to make it 800 ml volume. The complete solution was vigorously mixed at 500 rpm till 45 min at atmospheric condition at maintained pH level of 5–6. The resulting solution is called as seed solution which is used to develop the nucleation site of ZnO NSs on the WKF by seeding process.

2.4 Synthesis of ZnO Growth Solution

Preparation of growth solution comprises of synthesis of equimolar mixture of HMTA and ZNH. A growth solution of 10 mM is synthesized by mixing 10 mM of HMTA in 650 ml of distilled water for 20 min. Then 10 mM of ZNH powder was added into the solution and the complete mixture was stirred at 400 rpm and 30 °C temperature on a magnetic stirrer till 30 min while maintaining the pH level of 6–8. In the same manner remaining concentration of ZnO growth solution such as 30 mM, 50 mM, and 70 mM were synthesized.

2.5 Fabrication of ZnO/WKF/Epoxy Composites

The ZnO NSs/WKF epoxy composite is developed by synthesizing pretreated WKF samples into seed solution followed by growth solution. In the seeding process, the pretreated WKF pieces were soaked inside the seed solution for 15 min and then dried at 150 °C for next 15 min. This process helps to remove the solvents and propagate the adhesion of ZnO layer on the Kevlar surface. This cycle of seed treatment is done repeatedly for different set of seed cycle as designed in the experiment that is 2, 4, 6, and 8 cycles of seed treatment. The resulting sample is now used for growth treatment in which ZnO NSs were grown at the nucleated site of ZnO after seeding. In the growth treatment, the seeded samples were dipped inside the prepared growth solution and sealed inside a beaker then kept in a hot air oven at 100 °C for 8 h of hydrothermal treatment. After that, the samples were extracted from the oven and rinsed thoroughly with distilled water several times to halt the growth of ZnO NSs on WKF. The resulting sample is then dried in atmospheric condition for 48 h. In this way, different concentration of ZnO NSs WKF samples such as 10, 30, 50, and 70 mM were synthesized. Following chemical reactions were occurred during the hydrothermal synthesis of ZnO on WKF in the prepared seed and growth solution:

Reactions in the course of seeding phenomenon:

$$Zn^{2+} + 4OH^{-} \leftrightarrow Zn(OH)_4^{2-} \tag{1}$$

$$[Zn(OH)_4]^{2-} \leftrightarrow ZnO_2^{2-} + 2H_2O \tag{2}$$

$$ZnO_2^{2-} + H_2O \leftrightarrow ZnO + 2OH^{-} \tag{3}$$

$$ZnO + OH^{-} \leftrightarrow ZnOOH^{-} \tag{4}$$

Reactions in the course of growth phenomenon:

$$C_6H_{12}N_4 + 6H_2O \leftrightarrow 6HCHO + 4NH_3 \tag{5}$$

$$NH_3 + H_2O \leftrightarrow NH_4^{+} + OH^{-} \tag{6}$$

$$2OH^{-} + Zn^{2+} \leftrightarrow ZnO + H_2O \tag{7}$$

The composite panel of as prepared samples was fabricated using vacuum bagging method. In this method, five layers of each concentration of ZnO NSs WKF were used as reinforcement media and epoxy resin was used as matrix. Vacuum bagging was setup on a glass plate upon which five layers of each concentration was stacked with release fabric, peel play, and breather fabric. Now the complete staked ply was kept inside the prepared vacuum film bag and connections with vacuum pump and resin/hardener supply were made. The complete system was sealed properly and then vacuum pump was set up to run till a vacuum pressure of 60 kPa. The inlet and outlet of the system were sealed once required resin spread on the ply. The system was left for curing at atmospheric condition till 48 h to ensure complete curing. The

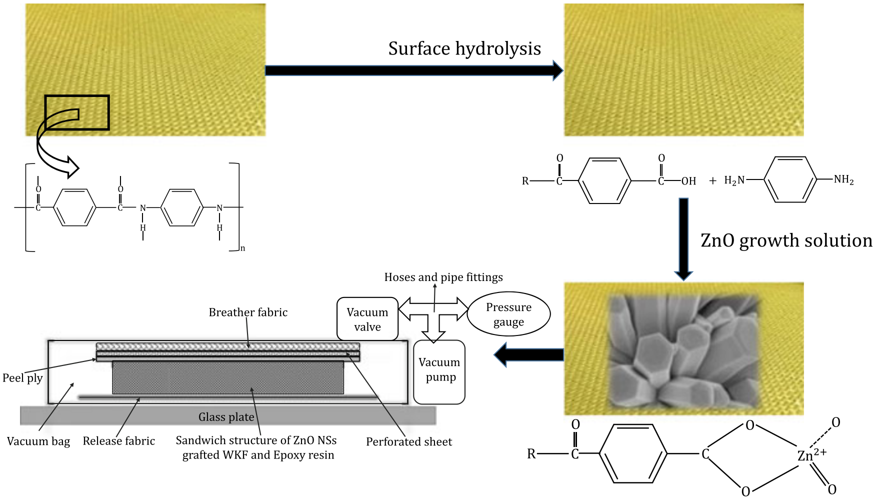


Fig. 2 Schematic diagram of fabrication of ZnO NSs/WKF/Epoxy resin hybrid composite

complete process of fabrication of ZnO NSs/WKF/Epoxy resin hybrid composite is illustrated in the Fig. 2.

3 Result and Discussion

Design of experiments was defined using software 'Minitab 16' (State College, PA, USA) in which hydrothermal parameters used to synthesize ZnO NSs on WKF fabric was setup. Three major factors such as seeding cycle, molar concentration, and growth duration were taken into account for complete hydrothermal technique. In this work, total duration of growth treatment was kept constant that is 8 h and the variation of remaining factors were analyzed. Total 16 set of experiments were designed and performed to examine the growth phenomenon of ZnO NSs on WKF. After analyzing the different reaction conditions along with their findings, it was found that the most successful growth of ZnO NSs on WKF were achieved at 8 number of seeding cycles and 8 h of growth treatment.

3.1 X-ray Diffraction

X-ray diffraction technique is used for the study of grown structure and crystal behavior ZnO nanoparticles using X-ray diffractometer containing Cu-Kα radiation. The XRD peaks of prepared ZnO NSs are illustrated in Fig. 3. The hexagonal wurtzite phase of ZnO NSs was verified by the XRD graph. The developed structure is of

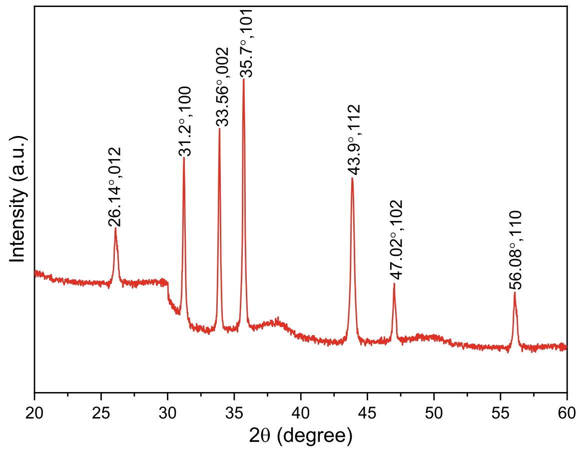


Fig. 3 XRD spectra of as prepared ZnO nanostructures on WKF

zincite crystal having chemical formula Zn_2O_2 which has hexagonal crystal system of space group P63 m c and space group number 186. The crystal parameters of developed ZnO are a = b = 3.25, c = 5.20, and $\alpha = \beta = 90°$; $\gamma = 120°$. ZnO nanoparticles developed on planes having (hkl) values (012) (100), (002), (101), (112), (102), and (110) indexed to angular position of 26.14°, 31.2°, 33.56°, 35.7°, 43.9°, 47.02°, and 56.08°, respectively, are in match with the JCPDS database No: 36–1461. The diameter of prepared ZnO NFs was derived from Debye–Scherrer expression [6]:

$$D = \frac{K\lambda}{\beta_D cos\theta}$$

where K is Scherrer's constant (generally K = 0.9), λ is the wavelength of X-rays, θ is the Bragg diffraction angle, and β is the FWHM (full width at half maximum) of the diffraction spectrum along the (101) plane. The β value is used to calculate average size of particle along (101) plane at 35.7° by applying Scherrer's relation. So by this method the average value of particle size is approximately 25 nm.

3.2 Morphological Studies of Grown ZnO NSs

The preliminary investigations regarding the growth of ZnO NSs on WKF were performed using Field Emission Gun-Scanning Electron Microscope (Zeiss Supra 40 make) at different magnification sizes at an operating voltage of 15 kV. Different synthesis conditions of hydrothermal reaction exhibits different results. It is clearly observed that the low seeding cycle have poor results even at high molar concentration of the ZnO. As the seeding cycle increases, the growth structure also improves. The

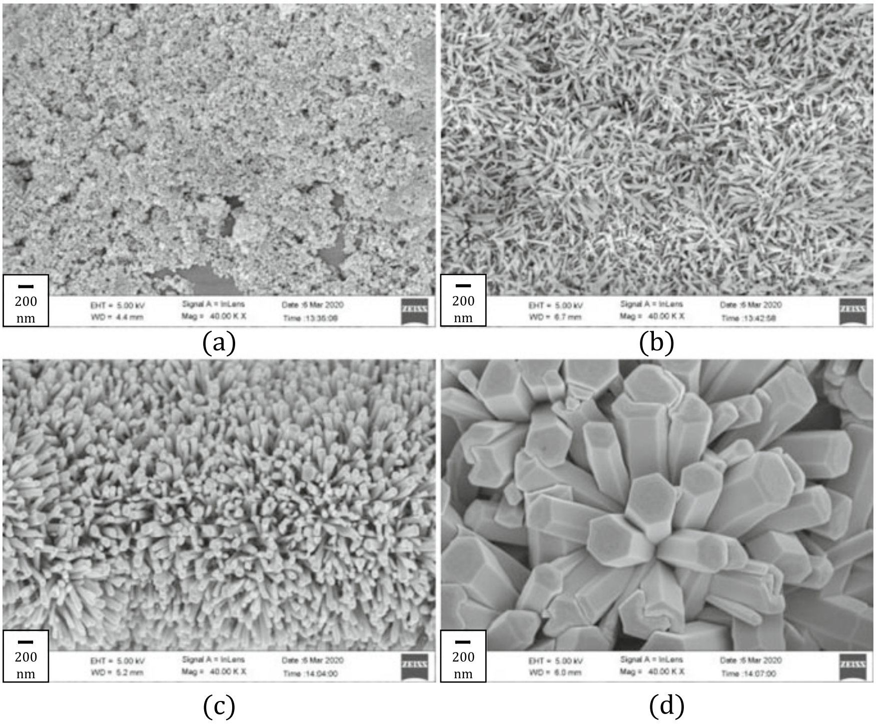
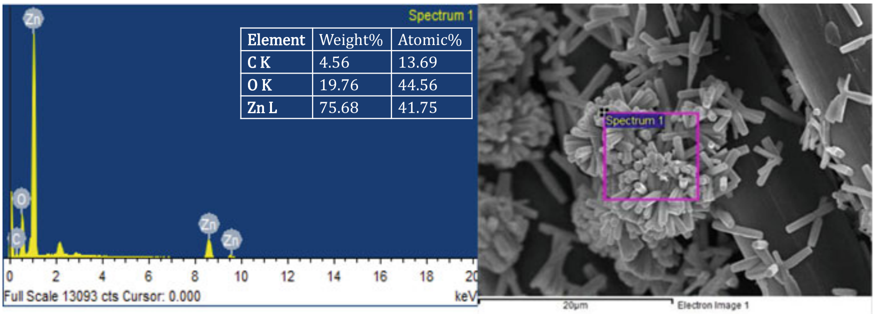


Fig. 4 FESEM micrograph of ZnO NSs grown on WCF under eight seeding cycle with 8 h of processing time **a** 10 mM, **b** 30 mM, **c** 50 mM, and **d** 70 mM

outcome of synthesis of ZnO nanorods with 8 number of seeding cycle corresponding to 30, 50, and 70 mM ZnO concentration is successful. However, the result of 10 mM ZnO concentration is moderate corresponding to 8 number of seeding cycle.

All the successful growth of ZnO NSs on WKF is clearly mentioned in the Fig. 4. ZnO nanorods of hexagonal cross-section were produced for the 8 number of seeding cycle and 70 mM molar concentration. It can be conclude that, at the sufficient concentration of growth solution and duration of growth, the nanostructures did not developed because of low no of seed treatment. These findings reveal that the seeding phenomenon is one of the prime factors for development of nanostructures. Results also established that the concentration of growth solution was not an important factor for the growth of nanostructures but by varying the concentration, different nanostructures such as nanoparticles, nanograss, nanowires, and nanorods can developed. The size of the developed nanostructures were also analyzed from the FESEM micrographs using 'Image J' software and it was found that the average length of ZnO nanorods grown corresponding to experiment numbers 14, 15, and 16 are in the range of 260–280 nm. The conformation of deposition of ZnO on the WKF surface was examined on a sample by Energy-Dispersive Spectroscopy (EDS) analysis is represented in Fig. 5a. It shows the presence of Zn, O, and C elements on the surface



(a) (b)

Fig. 5 **a** Energy-Dispersive Spectroscopy (EDS) analysis of ZnO grown on the WKF surface and **b** Combined image of grown ZnO NSs and WKF surfaces

of WKF strands. A combined FESEM image of as grown ZnO NSs and WKF surface is illustrated in Fig. 5b. After confirmation of ZnO nanostructures, the samples are used to make final composite panels with the help of the vacuum bagging technique.

4 Potential Applications

Different applications based on the ZnO 3D hierarchical architectures are photocatalysis, field emission, electrochemical sensors, biomedical, water treatment, and electrodes for lithium ion batteries [12]. Researches are going on to implement such distinguished properties of ZnO nanostructures into the field of high-performance composite materials. Some of the prominent applications of such composites are in aviation industries due to improved mechanical properties, especially impact strength. Continuous improvements of such materials will take the materials applications into different levels such as in robotics and artificial intelligence, sensors and biomaterials, micro-electronics and photonics, and defense and artillery [8]. Recent advancements in the fabrication of ZnO nanostructures on the carbon fibers lead towards the numerous applications in comparison to the natural carbon fibers [11]. Polymer-based nanocomposites are in the forefront of applications due to their more advanced development status compared to metal and ceramic counterparts, in addition to their unique properties. Still there is least application of nanocomposites in industries but advancements of these material from research to industry is growing and in coming few years it is expected to be extensive.

5 Conclusions

This paper briefly discussed about the evolution of crystalline ZnO nanostructures on woven Kevlar fiber strands via hydrothermal technique. In this study, different sets of experiments were examined by varying the seeding cycle and molar concentration to achieve optimum growth of ZnO NSs. In the initial process grass like nanowire morphology is obtained which turns into hexagonal nanorods with the increasing the seeding cycle, molar concentration, and hydroxyl (OH-) group concentration. The best results of ZnO NSs growth on WKF were achieved for the experiment number 14, 15, and 16. Functionalized Kevlar fiber coated with –COOH group reacts by the seed solution processing, and grows different nanostructures along the c-axis with help of the growth solution as explained by the FESEM and EDS analyses. The ZnO nanostructures started preparing their initiation site via seeding which affixed on the Kevlar fiber surface by pre-treatment. In the growth direction (c-axis), the growth rate was relatively affected by the molar concentration of HMTA and ZNH solution, but initiation of micron sized rods/structures leads towards non-uniformity. In the case of hydrothermal processing, seeding cycle, complete duration of fabrication of ZnO nanostructures have great impact on the resulting material. Surface density of the nanostructures varies with the variation in concentration and duration of two-step seed-growth phenomenon. Finally, hybrid composite panels were fabricated using vacuum bagging method for high-performance polymer composite applications. At the end, various potential application regions and scope of such hybrid ZnO nanocomposites are also discussed.

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Modeling and Optimization of RLT in Laser Trepanned ZTA Plate

S. K. Saini, A. K. Dubey, and B. N. Upadhyay

1 Introduction

Ceramic composites like Zirconia Toughened Alumina (ZTA) play a vital role in advanced technological industries. It possesses superior strength, fracture toughness, hardness and resistance to corrosion. These properties make ZTA suitable to manufacture armor, teeth, sleeves, heat exchangers, nozzles, etc. [1, 2]. Laser trepanning is a laser hole cutting/laser trepan drilling (LTD) process that is independent of processing materials characteristics. In laser trepanning, basic mechanisms of material removal are similar to other laser-based machining processes such as laser drilling or cutting. It is specifically used for cutting of larger holes (normally hole diameters more than 1.2 mm) [2] in difficult-to-cut materials. Though this process has the capability to cut different categories of difficult-to-cut materials whether it be metals and alloys, ceramics, polymers or composites, drilling defects like hole taper, heat affected zone and recast layer formation are seldom avoided. Therefore, researchers are trying to find out a suitable processing regime for different materials so that defects can be minimized.

Zhang et al. [3] conducted LTD on silicon nitride ceramic. They studied the effect of laser speed on the recast layer. They observed that the high pressure of assist gas (air) formed a fine recast layer. Bharatish et al. [4] developed a mathematical model for laser drilling of alumina using response surface methodology. They obtained lower heat affected zone and hole taper (HT) at optimum values of process parameters.

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Saini et al. [5] did laser drilling for yttria stabilized zirconia ceramic. They reported that maximum lamp current decreased the recast layer thickness. In another study, they studied material characteristics for LTD of ZTA [6]. Marimuthu et al. [7] conducted LTD on nickel superalloy. They revealed that fiber laser drilling yields better hole characteristics than conventional laser drilling. Liu et al. [8] performed LTD on non-oxide ceramic composite viz. carbon fiber reinforced silicon carbide. They tried to minimize the heat affected zone and taper using optimum values of parameters like pulse frequency, energy, pulse width and speed. The literature review discloses that only some researchers have studied the qualitatively recast layer of laser drilled hole for structural ceramics but rarely found the mathematical model and optimum value of recast layer thickness (RLT) specifically for a ZTA. In this paper, the authors find optimum values of input process parameters for RLT of laser trepanned hole in ZTA and developed a second-order regression model that is used as the objective function to discover the optimum set of process parameters. The optimum result has been tested by a confirmation experiment. The variation in RLT at non-optimum and optimum parameters levels is shown by SEM images.

2 Experimentation

Pulsed Nd: YAG laser trepanning has been performed on ZTA ceramic using a central composite design. The experimental setup of laser trepanning is shown in Fig. 1. The chemical composition of ZTA is represented in Table 1. Pulse width (X_1), pulse frequency (X_2), trepanning speed (X_3) and assist gas pressure (X_4) are considered as input parameters. The ranges and levels of input parameters are given in Table 2. Later, laser trepanned holes were perpendicularly cut to measure the RLT using a

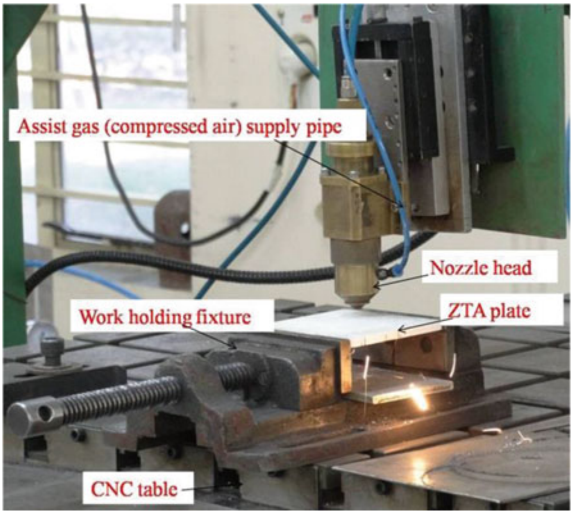

Fig. 1 Image of laser trepanning experimental setup

Table 1 Chemical composition of ZTA

Piece (%)	Al_2O_3 (79.64)	Zr (18.52)	Y_2O_3 (1.04)	MgO (0.012)	Na_2O (0.003)	SiO_2 (0.65)	Fe_2O_3 (0.033)	TiO_2 (0.002)	CaO (0.04)	K_2O (0.02)	Cr (0.04)

Table 2 Range and levels of input parameters

Input parameters	Ranges		Levels				
			−2	−1	0	1	2
X_1	4	12	4	6	8	10	12
X_2	8	14	8	8.5	9	9.5	10
X_3	5	40	5	10	20	30	40
X_4	8	10	8	8.5	9	9.5	10

scanning electron microscope (SEM) as shown in Fig. 2. Figure 2 shows the recast layer thickness. The average values of RLT are presented in Fig. 3 [6].

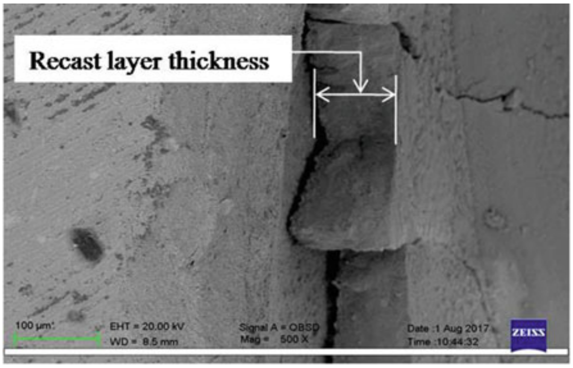

Fig. 2 Image of RLT in laser trepanned drilled hole of ZTA

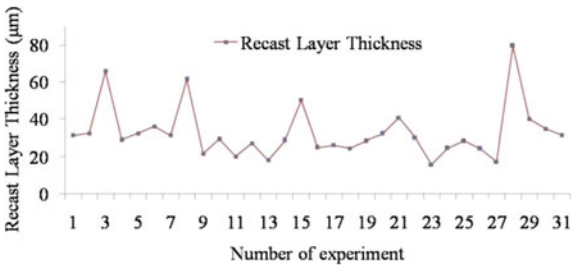

Fig. 3 Representation of RLT corresponding to the number of experiments

3 Results and Discussion

3.1 Modeling

Second-order polynomial regression model has been evolved for recast layer thickness [9]. The regression coefficient values of the regression model have been obtained using MINITAB® software. Equation (1) represents the developed regression model of RLT.

$$
\begin{aligned}
Y_{RLT} = & 112 + 0.484X_1 - 28X_2 - 1.37X_3 + 14.53X_4 + 0.949X_2^2 + 0.1038X_3^2 \\
& + 0.5006X_2X_3 - 0.857X_3X_4
\end{aligned} \tag{1}
$$

To examine the adequacy of evolved model, F-ratio and p-values of the source of regression have been determined by analysis of variance (ANOVA) result. The values of F-ratio for the source of regressions of response RLT are found more than critical F-ratio at 95% confidence level, while less than 0.05 found p-values. The values of coefficient of determination and adjusted coefficient of determination are 88.79% and 84.72%, respectively. This proves that experimental values of RLT are agreed in the evolved model. Hence, the developed regression model for recast layer thickness is reliable and adequate at a 95% confidence level.

3.2 Optimization

Genetic algorithm (GA) is a robust and evolutionary type of optimization technique [10]. The main aim of optimization is to achieve minimum recast layer thickness in laser trepanned hole. Therefore, the optimum value of recast layer thickness and their corresponding input process parameters have been determined using the inbuilt code of GA in MATLAB® software. Developed regression model of RLT, i.e., Equation (1) is used as the objective function, and the range of input process parameters (shown in Table 2) is used as the boundary of decision variables. Later, operating parameters of GA such as the number of generation (100), crossover probability (0.95), population size (40) and mutation probability (0.01) have been defined. After selecting all operating parameters, start the optimization solver. The optimization process has been terminated after the satisfaction of termination criteria. Figure 4 shows the optimum value of RLT (11.7104) and their input process parameters values ($X_1 = 4.278$, $X_2 = 8.042$, $X_3 = 28.371$ and $X_4 = 9.961$). Confirmation test value balanced with best RLT value that revealed improvement of 29%.

Further, variation between predicted and confirmed optimum value of RLT is found to be of 4.63% as shown in Table 3. This variation is also shown by SEM images (Figs. 2 and 5) of RLT at non-optimum and optimum parameter levels.

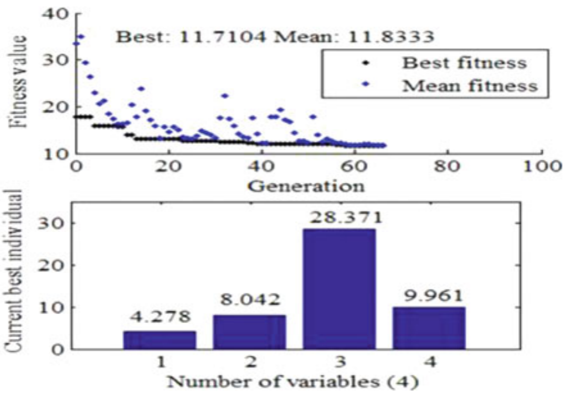

Fig. 4 Fitness and optimum values for recast layer thickness

Table 3 Optimum result for recast layer thickness

	Input parameters values				Response
	X_1	X_2	X_3	X_4	RLT(μm)
Best experimental value	8	11	20	9	15.735
Predicted optimum value	4.278	8.042	28.371	9.961	11.710
Confirmed optimum value	4	8	28	10	11.167
Improvement (%)					29.03
Variation (%)					4.63

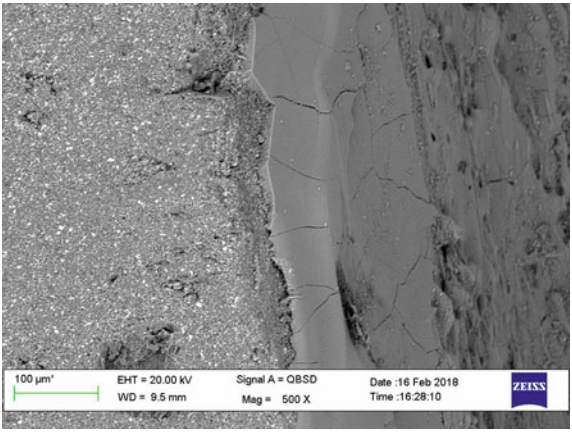

Fig. 5 Image for RLT at the optimum parameter level

4 Conclusions

The findings of the present research paper are given below:

- Laser trepanning has been performed on 6.0 mm thick ZTA using pulsed Nd: YAG laser.
- The developed mathematical model for RLT has been found reliable and adequate at a 95% confidence level. Coefficient of determination and adjusted coefficient of determination have been found to be 88.79% and 84.72%, respectively, which shows experimental values of RLT are agreed in the evolved model.
- The confirmed optimum value of RLT has been compared with the best experimental value that shows an improvement of 29.03%.
- Error between predicted and confirmation experiment has been found to be 4.63%.
- SEM images of RLT of laser trepanned hole surface at non-optimum and optimum process parameters' levels confirmed the improvement that means RLT reduced at optimum values of input parameters.

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Assessing Suitability of Obsolete Parts for Additive Manufacturing

Yeo Zhen Yong and Arlindo Silva

1 Introduction

Additive manufacturing (AM) or 3D printing (3DP) as it is popularly known is defined by ISO/ASTM52900 as "process of joining materials to make parts from 3D model data, usually layer upon layer, as opposed to subtractive manufacturing and formative manufacturing methodologies" [1]. This allows AM to be a "tool that offers increased "design freedom" and enables designers and engineers to create unique products that can be manufactured at low volumes in an economical way" [2]. This is suited for obsolete parts which are no longer produced and is not economically viable to utilize conventional manufacturing methods such as injection moulding, especially so if the overall product is obsolete or being phased out as well. For such parts, demand would be relatively lower and policies "could be eased for very slow-moving parts that could alternatively be printed on demand" [3], allowing companies to save on inventory costs, in terms of safety stock requirements and inventory space.

These advantages have led to an increasing interest in incorporating AM to create flexible production lines, with estimates "that 3D printing market could reach $180-490B by 2025" [4]. However, "a key challenge faced by companies that are considering adopting AM for spare parts manufacturing is the difficulty in identifying the most suitable parts which can be produced using AM" [5]. In a literature review done in 2019 by Chaudhuri, "only two studies have proposed methods for evaluating and selecting spare parts for AM" [6]. One focused on a top-down approach, ranking parts based on their potential value with data commonly available in standard information systems [7] while the other focussed on parts suitable for redesign and integration with other parts [8].

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A key aspect that has not been researched extensively is the alignment of company goals to the classification factors, i.e., current frameworks focus only on key objectives such as reducing inventory cost and downtime reduction, "these filtering criteria are overly rigid and eliminate the opportunities for AM redesign and added value" [9]. This was also prevalent in the literature review by Chaudhuri, where he agreed that there was "limited attention to examining the relationships between parts classification factors and company objectives" [6].

However, focussing on this criterion only will not be beneficial especially for users or companies new to or exploring AM technologies. They might not be clear on the available technologies, their limitations and benefits. Therefore, there is a need to establish a "detailed understanding of AM processes including the differences between them and their associated benefits and limitations [10]. In light of these, companies have turned to using software [11, 12] to identify potential parts for AM, providing information such as cost estimates and comparisons. However, this would often require the use of these standalone software and 3D models which may not be available or easily accessible for companies new to AM.

Therefore, in this paper, a 2-stage decision framework is proposed, aimed at assisting companies new to AM technologies identify obsolete parts suitable for AM without the use of 3D models. The first stage determines if the part is feasible and educates the companies on the current available technologies and their limitations in terms of size, material and machines, through a localized list of equipment available from their AM supplier. Stage 2 contains a weighted matrix that aims to align the companies' goals by allowing companies to understand what some current concerns are and select which weights are appropriate.

2 Assumptions—Defining Obsolescence

The first key assumption for this framework is defining the key attributes of an obsolete part. For this, we have to understand what are the current solutions available to replace obsolete parts. There are several methods in handling obsolete parts. This includes sourcing for FFF (Form, Fit, Function) equivalent parts, Lifetime buy, Last-time buy, Substitution or Redesign [13]. Therefore, the ability of AM allows companies to obtain FFF equivalent parts, while allowing for "design freedom" to redesign or substitute these obsolete parts. Parts that are suited to this shall not fall into the Lifetime buy or Last-time buy categories, signifying a need to identify parts that are obsolete in production and not available from other sellers.

Parts that are out of production may not be inherently obsolete if they are still covered by warranty. This would signify that if a part were to break down, it could still be obtained or replaced. Therefore, to ensure that parts are inherently obsolete, the part has to be also out of warranty, signifying that it would not be replaced or repaired by an external guarantor.

For this framework, an obsolete part is defined as one that is out of production and warranty. Any means to reproduce the part would revolve around selecting the type of manufacturing method for the part, be it traditional manufacturing or additive manufacturing.

3 Methodology

The framework (Fig. 1) comprises of a 2-stage review of parts. Stage 1 focuses on identifying potential parts in terms of: A. Obsolescence, M. Feasibility, S. Potential Inventory Savings, C. Properties of Part (Complexity and Criticality). This stage eliminates parts that are inherently unsuitable for additive manufacturing due to the limitations of current technologies available as well as non-obsolete parts. Companies whose goals revolve around reducing inventory costs may conclude with these findings. Whereas, companies which have other concerns can proceed with Stage 2, where they will be presented with a list of common concerns of additive manufacturing which they can utilize to align their goals through a weighted matrix to determine which parts are more suited for additive manufacturing.

3.1 Potential Value of Part for AM (F_1)

The potential value of the part for AM will determine whether and how suitable an obsolete part is for AM.

1. A part is determined to be suitable for AM if the part is Obsolete (A) and Feasible (M)

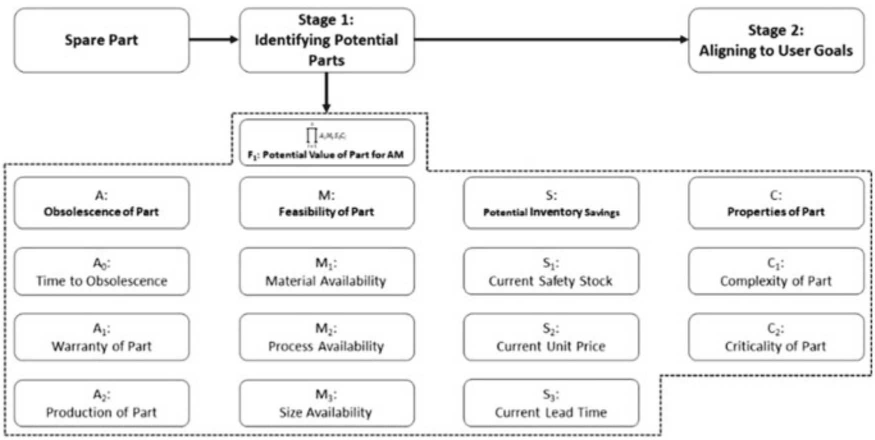

Fig. 1 Overview of part selection framework

2. How suitable is this part is largely dependent on S. Potential Inventory Savings but supplemented by C. Properties of the Part, particularly in terms of Criticality and Complexity, where possible Part Count Reduction (PCR) will give bonuses.

This final score is calculated by the equation:

$$F_1 = \prod_{i=1}^{3} A_i M_i S_i C_i$$

3.2 *Obsolescence of Part (*A*)*

For a part to be deemed obsolete, it has to be out of warranty (A_1) and out of production (A_2) as defined in the assumptions. In order to determine if fulfils both criteria, a new variable, Time to Obsolescence (A_0) has to be introduced.

Time to Obsolescence (A_0) is the average time taken by a company or organization in introducing in production processes, typically in weeks. This is crucial not only in identifying obsolete parts but parts entering obsolescence, hence allowing the user to plan for obsolescence.

Firstly, we have to determine if a part is **out of warranty (A_1)**. If its warranty period remaining is less than or equal to A_0, the part is defined as going out of warranty, a score of 1 is assigned to A_1, else 0.

Secondly, we have to determine if a part is **out of production (A_2).** If the remaining production period of the part is less than or equal to A_0, the part is defined as going out of production, a score of 1 is assigned to A_2, else 0, signifying that it fulfils one of the criteria of an obsolete part. The final score assigned to A is the product of A_1 and A_2. A score of 1 would signify that the part is going out of warranty and out of production, hence planning for its obsolescence and identifying new procurements methods should be initiated.

3.3 *Feasibility of Part (M)*

After determining if the part is obsolete, the next step is to determine if the part is feasible for AM or 3DP. In this, three main variables are considered, Material Availability (M_1), Process Availability (M_2) and Size Availability (M_3). A score of 1 is assigned to the variable if the part is feasible in that aspect, else a 0 is assigned; this can be referenced to the available dataset provided by the supplier (Fig. 2). The product of $M_{1,2,3}$ will determine if the part is feasible for additive manufacturing, i.e., a score of 1, would signify that all 3 variables are satisfied and the part is suitable for its respective AM process.

	Printing Methods*	Materials Available*	Current Available Largest Size*	Theoretical Size Limitation	Surface Quality (1-5) before Post-Processing	Post Processing Required	Minimum Wall Thickness
Polymers	Stereolithography (SLA)	Resins (Standard, Clear, Castable, Durable, High Temp, Dental)	177 x 101 x 254 mm	1500 x 750 x 500 mm	4 (Visible Layers)	Curing, Visible Layers	0.5mm
	Digital Light Processing (DLP)	Resins (Standard, Clear, Castable, Durable, High Temp, Dental)	160 x 100 x 180/230 mm	1500 x 750 x 500 mm	4 (Visible Layers)	Curing	0.5mm
	Multi Jet Fusion (MJF)	Nylon (PA 12, TPU 90A-01)	518 x 381 x 300 mm	518 x 381 x 300 mm	5 (Smooth)	Powder Removal	1.0mm
	PolyJet	Photopolymer Resin (RGD430, Agilus 30, Bio-compatible)	490 x 390 x 200 mm	490 x 390 x 200 mm	5 (Smooth)	Surface finishing	1.0mm
	Selective Laser Sintering (SLS)	Thermoplastic Powder (PA6, PA2210 FR, PP, PA-AF, PA 12, PA-GF)	340 x 340 x 600 mm	650 x 330 x 560 mm	2 (Grainy)	Surface finishing	0.7mm
	Fused Deposition Modelling	Thermoplastics (PLA, ABS, PET, PETG, TPU)	406 x 355 x 406 mm	900 x 600 x 900 mm	1 (Rough)	Surface finishing	0.8mm
Metals	Selective Laser Melting (SLM)	Aluminium Alloys, Stainless steel, Titanium Alloys, Cobalt-Chrome, Inconel	250 × 250 × 325 mm	500 x 280 x 360 mm	2 (Ra 12-16 μm)	Frequently required	0.4mm
	Wire Direct Energy Deposition (DED)	Aluminium Alloys, Stainless steel, Titanium Alloys, Cobalt-Chrome, Inconel	-	-	2	Frequently required	-
	Powder DED	Aluminium Alloys, Stainless steel, Titanium Alloys, Cobalt-Chrome, Inconel	-	-	3	Frequently required	-
	Binder Jetting	Metals (SS, Inconel alloy, Tungsten Carbide)	-	800 x 500 x 400 mm	5 (Ra 6 μm)	Yes to remove binder	2.0mm

Fig. 2 Example of materials, machines and processes available

3.4 Potential Inventory Savings (S)

Upon ensuring that the part is feasible for its respective AM process, a method has to be developed to rank which parts should be focused on first. In this framework, potential inventory savings is proposed to differentiate the values of potential parts in the first stage. The score for this variable S is the product of current safety stock (S_1), current unit price (S_2), current lead time (S_3). This is under condition that AM is able to provide a one-day lead time due to its print on-demand capability.

3.5 Criticality and Complexity of Part (C)

These variables highlight one of the key advantages of AM, the ability to reduce and customize parts, as well as one of the main concerns of AM, the lack of standards to verify the strength of parts.

Firstly, we will introduce the variable, **Criticality of the Part (C_1),** to address the lack of standards to verify the strength of parts. Although AM parts can be comparable to parts made by traditional methods through "the development of standard methods to test processes and parts" [14], the current lack of standards for verifying 3D printed parts is a major concern for users especially with the possibility of parts failing while in operation. "Extra work needs to be done to get regulations adjusted to be able to qualify 3D printed parts" [15]. In order to highlight this risk, parts that are less critical for operation should be chosen over more critical parts. Scores for this variable are defined from 1 to 3:

1. Safety Critical—Failure of the part may result in endangerment to human lives or compromise the safety of the machine.
2. Mission Critical—Failure of the part only results in the machine/product being non-operational, with no endangerment to human lives.
3. Non-Load Bearing or Non-Critical—Failure of the part has little to no effect to its operations or pose hazards.

Secondly, we will introduce the variable, **Complexity of the Part (C_2)**. A vital advantage of AM in producing spare parts is the possibility of AM-enabled Part Count Reduction (AM-PCR). "Design freedoms of material, geometry, and topology have extremely expanded and conventional manufacturing (CM) constraints (e.g., material difference and tooling accessibility) have largely been removed" [16] with the increasing viability of AM as a production method. This signifies a potential shift towards lower part counts, hence lesser inventory or safety stocks required.

Design files of conventionally produced parts may be unavailable, "(since it is the intellectual property of the supplier), nonexistent (as is often the case for obsolete spare parts), or insufficient (like in the case of 2D drawings)" [17]. This results in a need for a specialist or extra manpower to convert such files. Furthermore, parts may have to be functionally redesigned for AM to address its limitations such as overhangs as well as to achieve the same level of strength requirements, especially when an alternative material is used.

Therefore, the score for this variable, C_2, is given as follows from 0 to 1.5.

1.5	Possibility of AM-PCR or combination of parts with little redesign
1.0	Print as it is/little redesign needed
0.5	Some functional redesign
0	More parts required. This eliminates the main advantage of AM over conventional methods

3.6 Stage 2: Aligning to User Goals

In stage 1, a final score of F_1 is obtained for each part, largely based on feasibility, obsolescence and potential inventory savings. Users who may have other concerns with the AM production of parts can proceed with Stage 2 where common concerns of AM (Table 3) are introduced.

Step 1. Selection and ranking of 4 major concerns by user in line with their goals from Fig. 2 into Table 1 as V_1, V_2, V_3, V_4.

Step 2. Assigning weight to selected variables in Table 1. Total sum of weightage must be 100% or 1.

Table 1 Variable and weightage matrix (1st, 2nd, 3rd, 4th Weight = 40%, 30%, 20%, 10%)

Variable	V_1	V_2	V_3	V_4
Weightage	$W_1 = 0.4$	$W_2 = 0.3$	$W_3 = 0.2$	$W_4 = 0.1$

Table 2 Weighted matrix example for stage 2

	W_1	W_2	W_3	W_4	
Part no	Variable 1 (V)	Variable 2	Variable 3	Variable 4	Score
1	$V_{1,1}$	$V_{2,1}$	$V_{3,1}$	$V_{4,1}$	$F2_1$
2	$V_{1,2}$	$V_{2,2}$	$V_{3,2}$	$V_{4,2}$	$F2_2$

Step 3. Using Table 2 to assign scores to potential parts with F_1 more than 0 identified in Stage 1.

Step 4. Assign scores ($V_{i,j}$) between 1-5 for each part (Table 3).

Step 5. The final score for each part is calculated by the equation:

$$F2_j = \sum_{i=1}^{4} V_{i,j} \times W_i, \; where\ j\ is\ part\ number$$

Step 6. Part with highest score would be the best aligned to user's concerns. It should be considered first and sent for further evaluation to be printed.

4 Case Study

Three examples are presented to demonstrate the process of the framework (Fig. 3). These examples are based on a real-life case study where a company was exploring AM to replace possible components in a train cab. The parts are as follows.

1. Diffuser Ceiling Moulding (1.5–2.0 m Length)
2. Control Switches
3. Air-conditioning Nozzle.

In stage 1, the first step is to identify if the parts are obsolete (out of production and warranty). For parts 1 and 3 which are product specific components, these parts are already out of production and warranty as the train cab has been phased out, as highlighted by the company. However, for part 2, the control switches can be considered as generic components that can be easily obtained from third party sellers and hence it is not obsolete, resulting in a score of 1 in *A* for both part 1 and 3 and a 0 for part 2. However, there is the possibility where the switches are product specific

Table 3 Common concerns/variables and scoring

Variables	Description	Scoring
Surface quality	How important is surface quality to the application (1- High, 5- Low)	1- Human and machine interaction 2- Human interaction 3- Machine interaction 4- Little machine interaction 5- No interaction/Importance)
Unit cost	Estimated unit cost of the product using AM	1- Higher than previous 3- Similar 5- Lower than previous
Lead time	Estimated lead time in using AM to produce the part	1- Higher than previous 3- Similar 5- Lower than previous
Demand/quantity of part	What is the expected demand of the part in a year?	1–2 > 1000 3- 1000 pcs, 4–5 < 1000 pcs
Initial Start Up Costs	Start-up costs of procuring/preparing for AM (Includes machines, scanning/designing of files)	1- No AM processes in place (No relevant Machines/Designs available 2- Some AM processes in place/outsourced but no machines 3- AM processes in place with available designs of files 3- AM processes in place with available designs of files 3- AM processes in place with available designs of files 5- AM Processes fully in place (With Machines and Designs Available
Supply Risk	Are there any potential threats to the supply of this part currently?	1- No future/current threats to supply 2- Few future threats to supply 3- Few current threats to supply 4- Future and current threats to supply 5- Severe ongoing supply thread/ Disrupted supply
IP Challenges	Are there any challenges to overcoming the IP/Patents of the part?	1- Many challenges (Licenses, Lum-Sums, Technical Drawings) 2- Some challenges (Lum-Sums/Licenses) 3- One challenge/restricted usage (Lum-Sum, technical drawings, licenses) 4- Potential challenge/IP restrictions 5- Open-source/No challenges/IP restrictions
Printability	Is there a need to redesign or split parts to fit into the machine? (Are there available CAD files) Are there other technical requirements that need to be considered?	1- Redesign & technical requirements required 2- Redesign required 3- Technical requirements 4- Splitting of parts 5- Print as it is

Fig. 3 Parts examined for case study—**a** Part 1: diffuser ceiling moulding (1.5–2 m); **b** Part 2: control switches; **c** Part 3: air-conditioning nozzle

and hence, we shall consider that and assign an arbitrary value of (1) for part 2 as seen in Table 4.

Feasibility, M, of each part is considered next. Referencing to the dataset of available equipment in Fig. 2, the diffuser ceiling moulding (Part 1) will not be feasible as its maximum length of 2000 m is more than what is currently available (518 mm), a score of 0 is assigned to it, whereas materials and machines are available for the printing of the other 2 parts. Further investigation into part 1 will not be required.

The next component to be considered is potential inventory savings, $S_{1,2,3}$. However, data on these were not available. A score of 1 is provided to proceed with the review. The final variable to be considered in this case is the properties of the parts ($C_{1,2}$). The control switches can be printed as it is and hence is given a score of 1 for complexity (C_2). On the other hand, the air-conditioning nozzle comprises of 3 components, the directional nozzle, the vent housing and fasteners to mount both together. However, there is a possibility of integrating the directional nozzle with vent housing without the use of a fastener, resulting in a potential part count reduction and a score of 1.5 for part 3. In terms of criticality, a failure of the control switches (Part 2) could lead to machine failure as certain operations cannot be performed but may not pose any safety concerns. Failure of the air-conditioning nozzle will not result in any major operation failures, and the air-conditioning can still operate as usual, with the limitations being the direction the air is being blown. Therefore, a score of 2 and 3 is assigned to part 2 and 3 respectively. This results in a final score of 2 and 4.5 for the control switches and air-conditioning nozzle respectively (Table 4). The review may conclude here if the main objective of the company is to reduce inventory costs.

If the company were to proceed with Stage 2, there were a few main concerns highlighted as seen in Table 5, ranked with 1. Supply Risk, 2. Surface Quality, 3. Lead Time, 4. IP-Challenges. These (1–3) largely arise from the need to keep these trains running, with IP-Challenges being a potential issue that is commonly faced by many industries. Both part 2 and 3 are at supply risk due to future procurement of

Table 4 Stage 1 for case study

Part no	A	M	S_1	S_2	S_3	C_1	C_2	F_1
1	1	0	–	–	–	–	–	0
2	0 (1)	1	1	1	1	2	1	2
3	1	1	1	1	1	3	1.5	4.5

Table 5 Stage 2, weighted matrix for case study

	$W_1 = 0.4$	$W_2 = 0.3$	$W_3 = 0.2$	$W_4 = 0.1$	
Part no	Supply risk	Surface quality	Lead time	IP challenges	Score
3	4	3	4	2	3.5
2	4	2	5	2	3.4

parts are not available, leading to future supply risks. In terms of surface quality, it is essential for the control switches to have excellent surface quality due to human interaction whereas the nozzle has mainly machine-machine interaction, this results in a score of 2 and 3 as seen in Table 5. Lead time for the control switches would be faster due to it having a smaller physical dimension. Part 3 has a higher score of 4 compared to 5. Both parts would face some IP challenges in terms of obtaining the production license, leading to a score of 2. The final score F_2 is 3.5 and 3.4 for part 3 and 2 respectively. It is implied in both stages that part 3 is more suitable for AM and should be first explored for AM production.

5 Discussion and Future Work

Effectiveness of the framework is proven but a few limitations were highlighted. Data may not be available for potential savings as seen in the case study but such information is easily available to the company. However, if such data is unavailable, a placeholder of 1 could be used as the other two criteria in stage 1 still aids in the ranking of parts. Furthermore, other factors may be considered for stage 2 which is aimed at aligning company goals, however the top few were included in order to reduce the time needed to process such information especially for large datasets, achieving a balance between the number of factors and the time required to assess them. If needed, companies can include and vary the weightages of these factors to align their goals. Nevertheless, this is an area for potential future research.

Future improvement to additive manufacturing technologies could lead to new possibilities, reducing the impact of certain factors such as criticality, especially with qualifications of AM methodologies, as well as reduce concerns for lead time and surface quality. Hence, there will be a need to review, update and include new technologies into this framework in the future. However, this framework aims at assisting new companies and industries in manufacturing parts through AM by allowing them to understand which parts are suitable for researching and producing based on their own goals and concerns. Through this increased in understanding of AM processes and development of AM products, it would help establish a qualification and certification approach for these components [18].

6 Conclusion

In this paper, a framework was proposed to assess suitability of obsolete parts for AM. A definition of obsolete parts was identified, considering parts that are not suited for Last Buy or Lifetime Buy when planning for obsolescence, i.e., parts that are out of warranty and production. The framework consists of 2 stages, first identifying obsolete and feasible parts, ranking parts on potential inventory savings as well as criticality and complexity. Stage 2 adopts a user dependent weighted matrix to educate companies about the concerns of AM and align their goals accordingly. This addresses one of the main constraints in this field [6]. In the end, a case study was presented focussing on 3 parts of a train cab and discussed, limitations were highlighted and further works were discussed.

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Numerical Analysis on Influence of Clamping Force on Distortions of S235 Tube-Plate Joints

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1 Introduction

Tube-plate weld joints are widely used in power plants and petrochemical industries. Fusion welding is commonly adopted as a joining technique for them. During fusion welding process due to non-uniform heating and subsequent cooling, distortions are generated which causes reduction in buckling strength and affect dimensional accuracy and aesthetic values of the structures. In the past, various techniques have been developed to minimize weld distortion. One such technique is low stress no distortion (LSND) welding which has been developed at the Beijing Aeronautical Manufacturing Technology Research Institute in China in 1980s. Guan et al. [1] used LSND method in which localized cooling source, which trails the welding heat source. Due to the rapid cooling of weld region, tensile stresses were generated in the vicinity of the weld due to contraction. This decreased the plastic compressive strains due to heating; thereby stress levels and buckling tendency of the weld joint were reduced. Also, low temperature zones were obtained in the region of application of heat sink. Yang and Dong [2] studied the buckling induced distortions in thin low carbon steel plates during gas tungsten arc welding (GTAW) process integrated with liquid N_2 heat sink system. van der Aa et al. [3] investigated the response of trailing heat sink in conjugation with the moving heat source on distribution of residual stress

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during butt welding of thin AISI 316L steel plates. They applied CO_2 as a cooling medium. From the experimental observations, they found that significant difference in magnitude of residual stresses exists between samples joined by conventional welding process and DC-LSND technique. The compressive stress at a distance from the weld is minimized during DC-LSND process. It is concluded that heat sink cooling is effective in minimizing the buckling deformation of thin plates by altering the residual stress pattern. Guo Y. et al. [4] studied the response of trailing heat sink on residual stresses and distortions during pulsed laser welding of thin plates of Hastelloy C-276. For heat sink effect they used water which is atomized by compressed air through a nozzle. The fluid is applied on the bottom surface of the weldment. From the obtained results, they found that with increase in cooling intensity, out-of-plane distortions are reduced and at the same time transverse shrinkages were increased.

Welding sequencing is another promising method for reducing distortions by optimising the sequence during multi-pass welding. Gannon et al. studied the effect of weld sequences on distortions during gas metal arc welding (GMAW) of flat-bar SM400A stiffened plates. Chen et al. [5] investigated the influence of weld sequencing on welding deformation and residual stresses using a finite element thermo-elastic–plastic model. They found that by optimizing the weld sequence, welding distortion and residual stresses can be minimized significantly. Yi et al. [6] presented the optimum welding sequence to control the welding deformation and residual stresses during double-pulse metal inert gas (MIG) welding of AA6061-T6 automobile bumpers. Vetriselvan et al. [7] studied the out-of-plane distortion in multi-pass circumferential welding under three different welding sequences. They found that welding directions and sequences influence the out-of-plane distortion. However, all these methods involve additional process parameters which cause the process more complex and costly.

In spite of, efforts put by researchers and scientists, one parameter i.e. effect of clamping conditions on distortions has not been explored in most research. There are only few literature available on influence of clamping conditions on distortions in weldments. Schenk et al. [8] reported the effect of different clamping conditions on final distortion of GMA welded thick S355 T-joints. It is shown that clamping conditions has a strong influence on cooling rate and angular distortion. Trummer et al. [9] studied the effect of different clamping forces on residual stresses and distortions during friction stir welding of AA2198-T8. It is found that higher clamping forces lead to lower distortions. Schenk et al. presented numerical study on influence of clamping conditions on the distortions generated during MIG welding of DP600 joints. They have concluded that the magnitude of residual stresses and buckling distortions is reduced by increased clamping duration.

Finite element (FE) method has been popularly adopted technique for analysing thermo-mechanical behaviour of weldments during fusion welding. Chiocca et al. [10] developed a FE model to evaluate the residual stresses in tube to plate structure welded by single pass gas metal arc welding (GMAW) process. A sequentially uncoupled thermo-mechanical FE model has been developed to predict the residual stresses tube to plate welded joint. Element “Birth and Death” technique along with temperature dependent material properties has been employed in the FE model.

Choicca et al. [11] presented a numerical and experimental study of residual stresses and distortions generated in pipe-to-plate welded joint of S355JR carbon steel fabricated by GMA welding process. An uncoupled thermal-structural analysis has been performed using FE ANSYS software to evaluate strains, stresses and temperature. From the obtained results, it is concluded that the 3D FE technique is effective in determining the residual stresses in pipe-to-plate weld joints. Dengyu et al. [12] carried out the numerical analysis using finite element simulation software SIMUFACT WELDING for analysing the thermal–mechanical behaviour of low alloy high tensile steel tube-plate joints. In the mesh model, fine mesh have been used near the weld zone, while coarse mesh were used far from the weld. Non-linearities because of temperature dependent material properties, heat transfer coefficients and latent heat are taken into consideration during FE thermal-structural analysis. Han et al. [13] investigated the residual stresses for welding of tube-pate structure with T-shaped sections using finite element ANSYS software. Goldak's ellipsoidal volume heat source is utilized for the design of the weld pool.

From the literature survey, it is found that there are only few literatures are available and more work is still required to analyse the effect of clamping force during welding of tube to plate joints. In this paper, a coupled thermal-structural finite element model is presented using the SIMUFACT welding software to study the effect of clamping forces and clamping time during welding tube to plate joint. Four different cases were considered in this work as case I (a): Clamping force of 50 N was applied and activated till the execution of welding process (28 s) of tube to plate joint, case I (b): Clamping force of 50 N was applied and activated till the execution of cooling cycle (300 s) of tube to plate joint, case II (a): Clamping force of 100 N was applied and activated till the execution of welding process (28 s) of tube to plate joint, case II (b): Clamping force of 100 N was applied and activated till the execution of cooling cycle (300 s) of tube to plate joint.. The effect of convection and radiation boundary conditions and temperature dependent material properties is considered in the model. To simulate the heat source movement, Goldak's double ellipsoidal heat source model is implemented.

2 Thermal Analysis

The governing heat conduction equation in three dimensional body for transient nonlinear heat transfer analysis can be written as [14]

$$k\left[\frac{\partial}{\partial x}\left(\frac{\partial T}{\partial x}\right)+\frac{\partial}{\partial y}\left(\frac{\partial T}{\partial y}\right)+\frac{\partial}{\partial z}\left(\frac{\partial T}{\partial z}\right)\right]+q_g=\rho c_p\frac{\partial T}{\partial \tau} \tag{1}$$

where k (W/m °C), $\dot{q}_g$(Wm^{-3}), ρ (kg/m^3), c_p (kJ/kg °C) are the thermal conductivity, rate of internal heat generation, density and specific heat respectively. T is the temperature at point (x, y, z), and τ is time in seconds.

Heat dissipation due to convection and radiation are considered in our investigation and are employed as boundary conditions during the thermal analysis. Heat loss due to convection was modelled by Newton's law of convection as shown in Eq. (2), while heat loss due to radiation was modelled by Stefan-Boltzmann's law governed by Eq. (3):

$$q_{con} = -h(T_s - T_\infty) \tag{2}$$

$$q_{rad} = -\varepsilon\sigma\left(T_s^4 - T_\infty^4\right) \tag{3}$$

where h is the convective film coefficient (Wm^{-2} °C), T_s is surface temperature (°C), T_∞ is surrounding temperature (°C), ε is surface emissivity, and σ is the Stefan-Boltzmann constant. In SIMUFACT™ software, the value Stefan-Boltzmann constant used is 5.67×10^{-8} (Wm^{-2}). The convective film coefficient value and emissivity values assumed in the thermal analysis are 20 Wm^{-2} °C and 0.6 respectively [15]. The initial temperature assumed in the simulation is 28°C. The welding process parameters adopted in this work is as shown in Table 1 [15].

For performing the numerical simulation of the welding process, Goldak's double ellipsoidal heat source model as shown in Fig. 1 is employed. The power density distribution in the front and the rear portion is expressed as [16, 17]:

$$q_{f,r}(x, y, z, t) = \frac{6\sqrt{3} f, r Q}{ABC\pi\sqrt{\pi}} \exp\frac{-3x^2}{b^2} \exp\frac{-3[y + s * (\tau - t)]^2}{a^2} \exp\frac{-3z^2}{d^2}\left[\mathrm{J}/\left(\mathrm{m}^3\mathrm{s}\right)\right] \tag{4}$$

Table 1 Welding process parameters

Welding voltage, V (V)	17
Welding current, I (A)	100
Weld speed (mm/s)	5

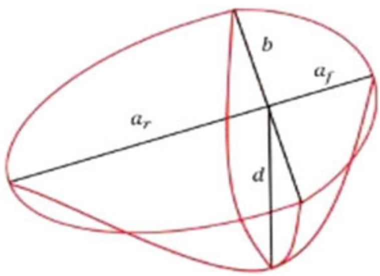


Fig. 1 Configurations of double ellipsoidal heat source model

where x, y, z are the local coordinates, τ is lag of heat source at time $t = 0$, $Q = \eta VI$ is the total heat input, η is heat source efficiency and was assumed as $\eta = 90\%$. F_f and F_r are the fractions of the heat deposited in front and rear quadrants respectively. The constants a, b, d are heat source parameters. The values of heat source parameters used in the simulation are $a_f = 1.96$ mm, $a_r = 7.2$ mm, $b = 2.77$ mm and $d = 3.77$ mm [15]. Based on the welding speed total 28 solution steps were executed to model the heat source movement during the welding process. Finally, last step of 300 s was enacted to simulate cooling of weld tube-plate welded structure to the surrounding temperature.

3 Finite Element Analysis

In the present study, the finite element analysis was performed on the weld structure as shown in Fig. 2. The finite element mesh model of the plates is illustrated in Fig. 3. The thermo-mechanical FE simulation was performed by using SIMUFACT™ software. To discretize the geometry, 'hexahedral' elements were used for executing thermal and mechanical analysis respectively. The size of the element used in the analysis is $2 \times 2 \times 2$ mm^3. Total 3267 elements were used to simulate both thermal and

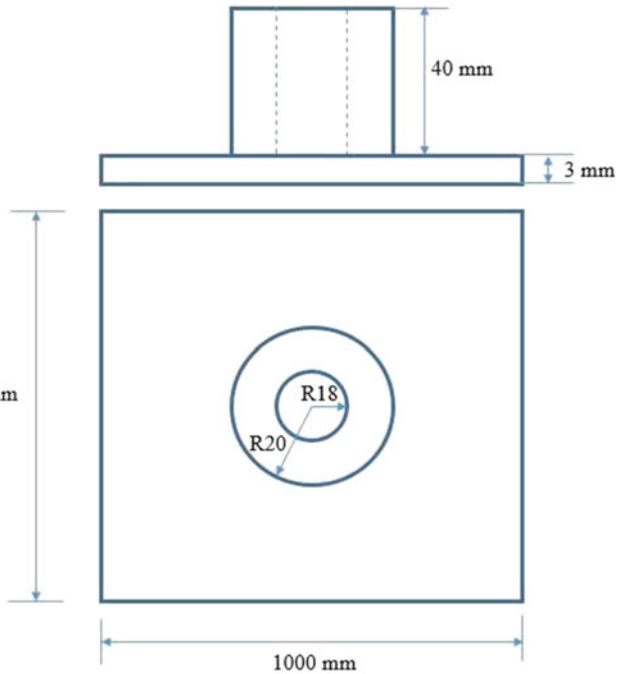
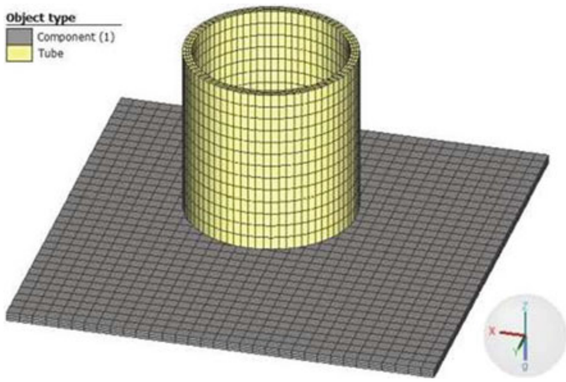


Fig. 2 Geometric model

Fig. 3 Finite element mesh



structural analysis. With reference to FE analysis following simplified assumptions were made as:

(1) Temperature dependent thermal, mechanical and physical properties were used.
(2) Effect of latent heat was considered in the analysis.
(3) "Element death and birth" technique is adopted to simulate the deposition of filler metal.
(4) Properties in the liquid region was neglected.

The S235 structural steel and S316L stainless steel materials were selected respectively as base material and clamping material for the thermo-mechanical analysis. The chemical composition (wt%) of S235 material and filler material are listed in Table 2. Since the temperature dependent properties affects the thermo-mechanical welding simulation results, temperature dependent properties of S235 material were employed for the FE simulation as shown in Table 3 [15]. Constant value of latent heat and Poisson's ratio as 256,400 J/kg and 0.3 respectively was used in the analysis. The material was modelled as elasto-plastic solid with isotropic strain hardening model.

To obtain the numerical solution for temperature distribution and distortions, the finite element analysis was performed in two steps. Initially, a non-linear transient thermal analysis was carried out to find out temperature histories on weldments during the welding process. Further, structural analysis was performed with the temperatures obtained from the thermal analysis applied as 'body force' loads. For the welding process, the total strain increment can be represented as summation of plastic strain rate ($d\dot{\varepsilon}_{ij}^{E}$), elastic strain rate ($d\ \dot{\varepsilon}_{ij}^{P}$) and thermal strain rate ($d\ \dot{\epsilon}_{ij}^{TH}$) as [18]:

Table 2 Chemical compositions of the S235 material and filler material (wt%)

Element	C	P	Fe	Mn	S	Si	Cr
S235	0.25	0.05	0.30	1.60	0.05	0.05	0.30
SG2 wire	0.08	–	97.57	1.50	–	0.85	–

Table 3 Temperature dependent properties of S235 structural steel

Temperature (°C)	25	200	400	600	700	750	800	850	1300
Density (Kg/m^3)	7852.17	7785	7740	7660	7620	7590	7580	7540	7397.4
Specific heat (J/g. K)	0.445	0.516	0.617	0.789	0.949	0.935	0.852	0.601	0.670
Thermal conductivity (W/m °C)	54.93	50.62	43.57	36.77	34.15	33.11	32.27	27.71	33.26
Coefficient of thermal expansion (1/K) $\times 10^{-5}$	1.31	1.43	1.5	1.52	1.54	1.54	1.6	1.625	2.5
Young's Modulus (MPa)	210,627	200,000	186,666.66	39,333.33	27,333.32	140,000	133,333	119,999.98	75,692.4

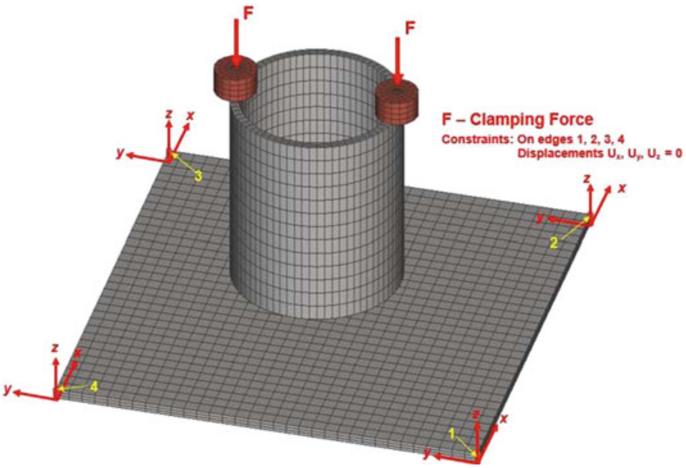


Fig. 4 Mechanical boundary condition

$$d\varepsilon^{Total} = d\dot{\varepsilon}_{ij}^{E} + d\dot{\varepsilon}_{ij}^{P} + d\dot{\varepsilon}_{ij}^{TH} \quad (5)$$

In the FE structural analysis 'Cylindrical Type Fixed Supports' boundary conditions were applied on tube to plate weld structure as illustrated in Fig. 4. The radius and width of both the clamps used in the FE simulation was 5 mm. Two different clamping forces as 50 N and 100 N are applied on the tube to plate weld joints. Total elapsed time for thermo-mechanical computation for case I (a) and case II (a) is about 23 min and 25 min for case I (b) and case II (b). The analysis was performed on work station computer with an Intel core i7-8700 CPU, 16 GB of RAM.

The transient temperature distribution in tube-plate weld structure at time step of 4 and 25 s in case I (a) and case II (a) is shown in Fig. 5. It is observed that the temperature around the heat source increases quickly from surrounding temperature of 28 °C to peak temperature of 1510 °C in the weld pool, indicating melting of material in the fusion zone. From figures, it can be seen that the peak temperature at 4 s time interval in both the cases is same and the effect of clamping on heat transfer rate is negligible. After 28 s, the movement of heat source is turned off which results in gradual decrease in temperature. The temperature profile after 28 s is mainly effected by the radiative and convective boundary conditions.

Figures 6, 7 and 8 show the numerically evaluated displacement in x-direction, z-direction and y-direction for case-I (a), case-I (b), case II (a) and case-II (b) respectively. From figures, it is seen that the maximum x-direction displacement in case I (a) and case II (a) are 0.27 mm and 0.26 mm respectively, maximum z-direction displacement in case I (a) and case II (a) is 0.07 mm and the maximum y-direction displacement in case I (a) and case II (a) is 0.27 mm. Similarly, the maximum x-direction displacement in case I (b) and case II (b) are 0.28 mm and 0.27 mm and maximum z-direction displacement in case I (b) and case II (b) is 0.39 mm and 0.33 mm and maximum y-direction displacement in case I (b) and case II (b) is

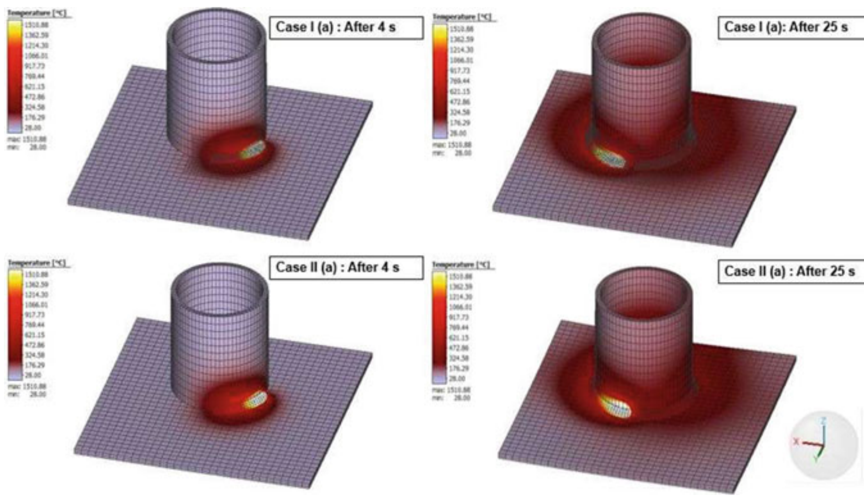


Fig. 5 Transient temperature at time steps of 4 and 28 s

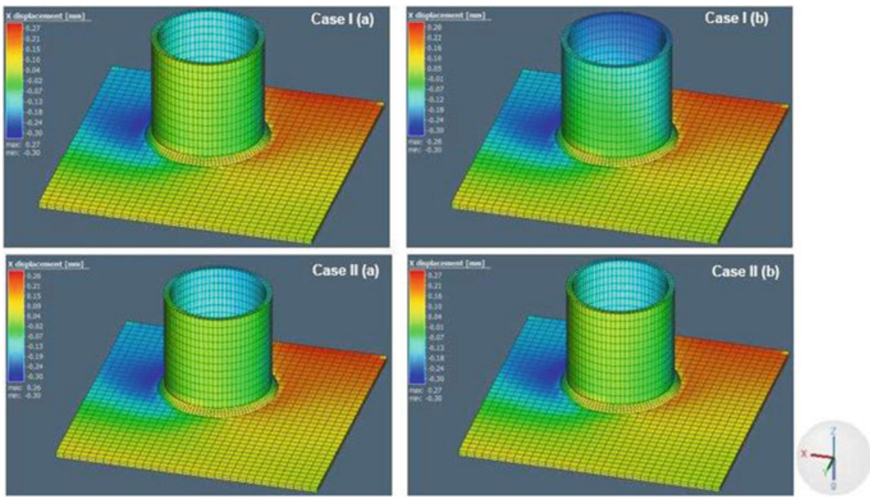


Fig. 6 Contour plots of x-displacement in case I (**a**), case I (**b**), case II (**a**) and case II (**b**)

0.29 mm and 0.28 mm. This shows that use of clamping force facilitates in reduction of distortion in z-direction; however, its effect in minimizing the shrinkages in other direction is not significant. From the figures, it is also clear that not only the clamping force but the clamping time also significantly affects the amplitude of distortions in tube to plate structures.

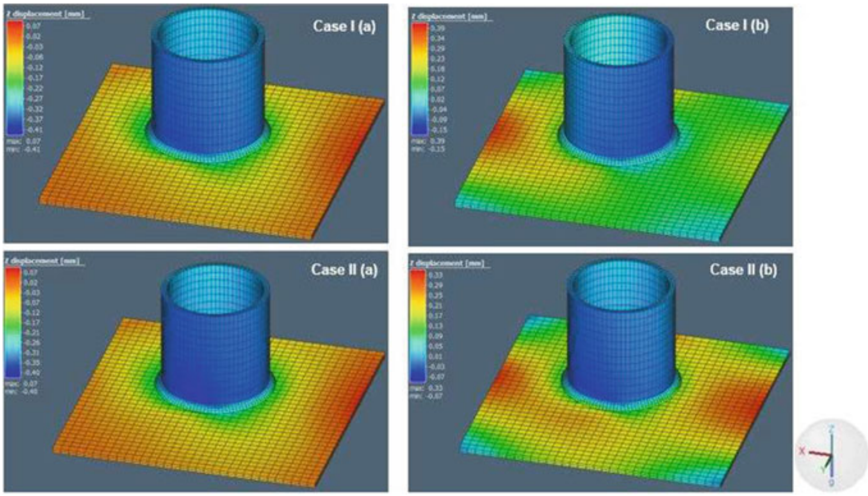


Fig. 7 Contour plots of z-displacement in case I (**a**), case I (**b**), case II (**a**) and case II (**b**)

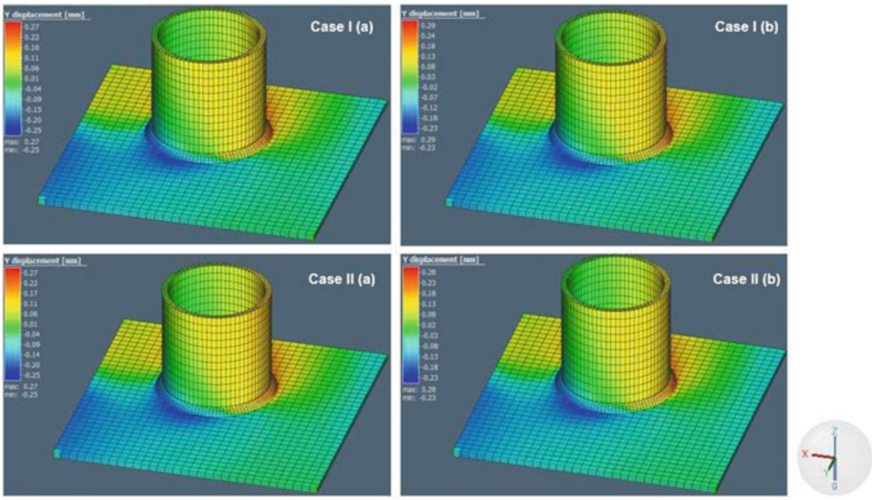


Fig. 8 Contour plots of y-displacement in case I (**a**), case I (**b**), case II (**a**) and case II (**b**)

4 Conclusions

In the present study, a FE simulation study for tube-plate welded structure is carried out. The conclusions from the present work are as follows:

- The maximum temperature noted during the welding is 1510 degrees Celsius, and the heat transfer is predominantly due to conduction.

- A suitable FE model is proposed to perform thermo-mechanical analysis with Goldak's double ellipsoidal heat source can be employed to determine the distortions in tube-plate structures.
- Clamping force and clamping time influence the final distortion in tube-plate weldments.
- Clamp releasing after cooling to the ambient temperature reduces the angular distortion.

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Development of an Ultra-High Speed Micro-Milling Center: An FEM Approach

Arnab Das and Vivek Bajpai

1 Introduction

The growing application of high accuracy miniaturized components has endorsed the necessity of ultra-precision micromachine tool in several industries like electro-optics, automotive, biotechnology, aerospace and information technology [1]. Micro-milling is one of the most versatile micromachining technologies capable to produce complex 3D features and mirror finish on several difficult-to-cut materials [2]. However, low tool stiffness and low material removal rate (MRR) have restricted the application of micro-milling technology. High-speed micromachining is a comprehensive means to those challenging issues. This technology required high-speed spindle which is a major source of cutting vibration in the micro-milling machine [3]. Due to cutting vibration, the accuracy, precision and surface finish of the miniaturized products can completely deteriorate. Additionally, chatter may develop due to cutting vibration leading to damage of the cutting tool [4].

There are several approaches to develop the machine tool for high-speed micro-milling in the last two decades. Luo et al. [5] developed a bench-top ultra-precision machine tool (UPM) where miniaturized components can be machined with high accuracy. The machining accuracy was highly dependent on the spindle accuracy, stage accuracy and structural damping. Huo et al. [6, 7] proposed a closed-type machine structure for better stiffness and damping capability of high-speed micro-milling machine tool. However, medium to high frequency vibration still exists within the range of high-speed spindle. Das et al. [8] developed a vibration-free highly rigid machine structure for this purpose to absorb vibration during high-speed micro-machining. This structure can be applicable for ultra-high speed micromachining as

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well. However, the configuration for spindle arrangement with linear stages to reduce vibration was not yet discussed in this study.

This paper describes two different configurations of ultra-high speed micro-milling machine tool. The micro-milling machine consists of an ultra-high speed spindle having a maximum rotational speed of 140000 rpm and ultra-precision linear stages. The moving components have been accommodated in a developed rigid-type machine structure. In Configuration A, the spindle has been attached to the linear stage assembly. However, the spindle was attached to the upper block of the machine structure for Configuration B. The purpose was to minimize the cutting vibration for the micro-milling machine. Both the configured models had undergone finite element analysis (FEA) to evaluate the static stiffness, natural frequencies and dynamic stability. Eventually, the best configuration has been adopted for the ultra-high speed micro-milling operation.

2 Model Validation

The development approach is based on finite element modeling. Therefore, the initial step was to validate the model. A provisional machine tool has been developed for validation purposes which was assembled with high-speed spindle and linear stages. The model of the temporary machine tool has been replicated in AutoCAD 3D which is shown in Fig. 1a. The CAD model of the unassembled mild steel frame had undergone modal analysis simulation (shown in Fig. 1a) in the ANSYS workbench. The mild steel frame was excited by the impact hammer during experimental modal analysis. Roving accelerometer (Bruel & Kjaer make) technique was applied for signal collection. The frequency response function (FRF) was generated by photon + dynamic signal analyzer and processed in MEScope Ves software. The results of the experimental modal analysis were almost similar to the simulation result where

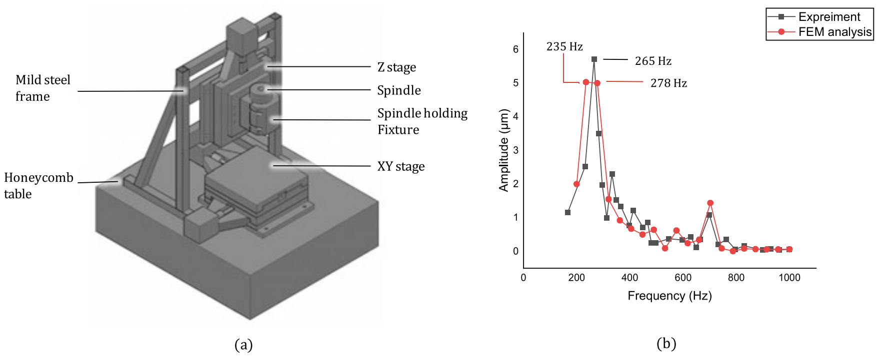

Fig. 1 **a** CAD model of the temporary machine tool made for model validation and **b** Comparison of frequency waveform generated in FEM and cutting experiment along the radial direction

a maximum deviation of 17% was found in the third mode. Therefore, the model was further expanded. Furthermore, the model had undergone harmonic response analysis simulation considering a set of constant forces on the tip of the tool holder along each direction. The harmonic plot has been generated in ANSYS. It shows the maximum amplitude of vibration 5.03 μm at a frequency of 235 Hz along the Y-direction. Additionally, the cutting experiment has been performed in the machine tool varying the rotational speed of the spindle from 10,000 to 60,000 rpm at a constant interval. The chip load was kept constant for each run at 1 μm. For this purpose, the feed rate has been varied accordingly. The depth of the cut was set at 50 μm. A two flute milling cutter of cutter diameter 1 mm was used for machining and the workpiece was mild steel. The cutting vibration data has been captured by accelerometers mounted on the outer casing of the spindle along the radial section. It shows the maximum amplitude of vibration 5.7 μm along the radial direction at a frequency of 265 Hz. The plot of cutting vibration was almost similar as achieved in harmonic response analysis. Hence, the model was validated. The comparison of the experimental waveform of cutting vibration and harmonic response data has been plotted in Fig. 1b.

3 Model Configurations

The ultra-high speed micro-milling machine consists of an ultra-high speed spindle (Model HT 45 S 140, Ibag make) which has a maximum rotational speed of 140,000 rpm. Table 1 depicts the specifications of the spindle. The spindle is attached to a spindle holding fixture made of mild steel. Additionally, ultra-precision linear stages have been incorporated into the machine tool. Newport make One-XY100 model has been selected for linear movement in the X-Y-directions. Another Newport make GTS30V model has been selected for linear movement along the vertical direction. The vertical stage has been attached over the X-Y stage to generate a combined linear movement along all three directions. Table 2 depicts the technical specifications of all the motorized linear stages. All the moving components have been accommodated in a machine structure made of natural granite. The machine structure is a closed-type highly rigid structure which consists of a machine bed, two frame columns and an upper block. In this study, two different configurations of micro-milling machine tool have been experimented. The first one is Configuration A, where the spindle assembly is attached to the linear stages. The cutting is performed along horizontal (Y-direction) in this case. Another one is Configuration

Table 1 Technical specifications of the ultra-high speed spindle

Spindle speed (rpm)	Maximum torque (N-cm)	Maximum power (kW)	Cooling system	Tool change
10,000–140,000	4.3	0.63	Liquid	Pneumatic

Table 2 Technical specifications of the linear stages

Model	Movement direction	Travel range (mm)	Accuracy (μm)	Minimum incremental motion (nm)	Load carrying capacity (N)	Maximum speed (mm/s)
One XY10	X-Y-axis	90	±0.5	50	120	200
GTS30V	Z-axis	30	±0.37	100	40	10

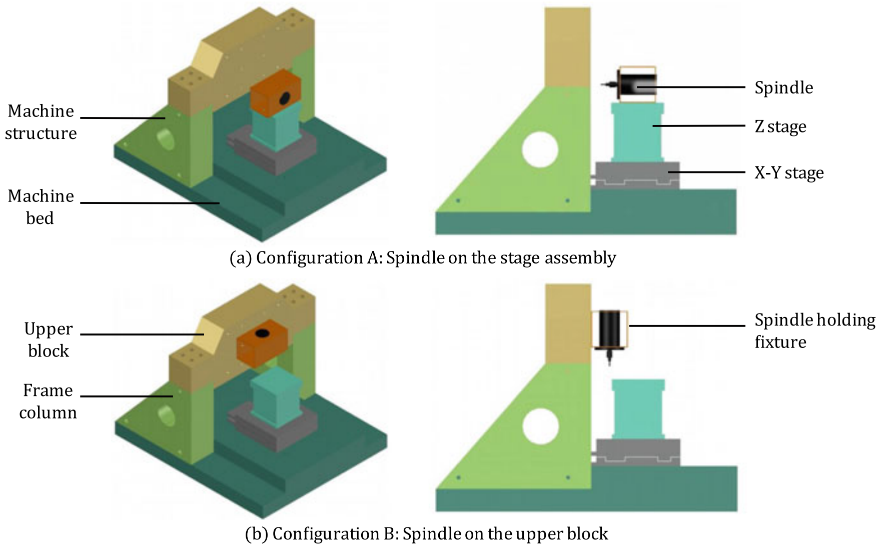

Fig. 2 Two configurations of ultra-high speed micro-milling center

B, where the spindle assembly is attached to the upper block of the machine structure. The cutting is performed vertically in this configuration. The static stiffness, natural vibration and dynamic stability have been studied for both the configuration. Based on the performance, the best configuration has been adopted for the ultra-high speed micro-milling operation. Figure 2 illustrates both the configurations of the ultra-high speed micro-milling machine tool.

3.1 Modeling of the Linear Stages

The linear stages consist of precision cross roller bearing with DC motor power supply and low friction lead screw drive system to generate high precision linear movement. The models of the linear stages have been generated for FEM analysis. However, it is difficult to generate the actual rolling interface for the linear stages. Therefore, a spring element has been considered between each interface of the linear

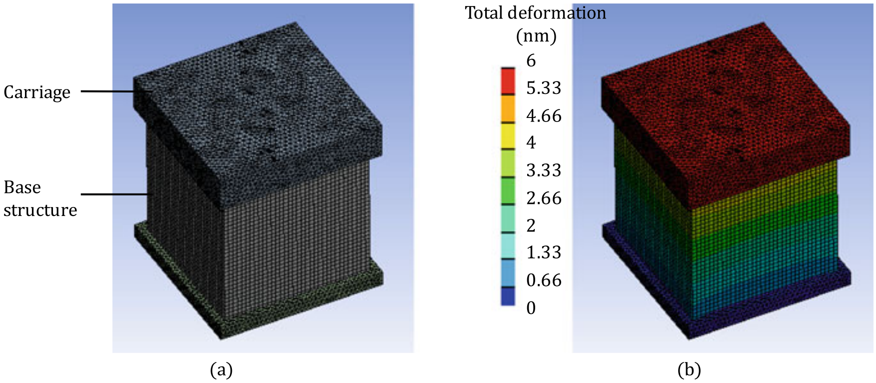

Fig. 3 **a** Model of the vertical linear stage generated for FE modeling and **b** Static performance of the vertical linear stage

stages. One dimensional spring element has been considered for that purpose. Static structural analysis has been performed to evaluate the stiffness of the spring element. The linear stages have been given the maximum permissible load on the carriage. The estimated stiffness was used in the FE analysis of the micro-milling machine tool. Additionally, the contact interfaces of the linear stages are metal to metal contact. Therefore, a constant damping ratio (0.04) has been considered for each interface. Figure 3a represents the model of the vertical linear stage whose FE model has been represented in Fig. 3b.

4 Performance Evaluation of Both the Configurations in FEM

4.1 Static Structural Analysis

The static performances of both the configurations have been evaluated by static structural analysis. A set of constant static forces have been applied at the tip of the tool holder along all three directions. The bottom of the machine structure has been constrained in both cases. The stiffness of the tool tip has been evaluated for both the configurations along the three directions. In FEM, it is difficult to consider the actual bearing configuration of the spindle. Therefore, the solid bearing has been considered for the bearing, and all the bearing parameters such as bearing stiffness and damping constants have been considered according to the actual bearing parameters of the spindle. Figure 4 depicts the stiffness of the tool tip calculated from static structural analysis in ANSYS for both the configurations. It shows that the stiffness of Configuration B is not much varied along all three directions. However, the stiffness of Configuration A shows larger variation along all directions. The stiffness along

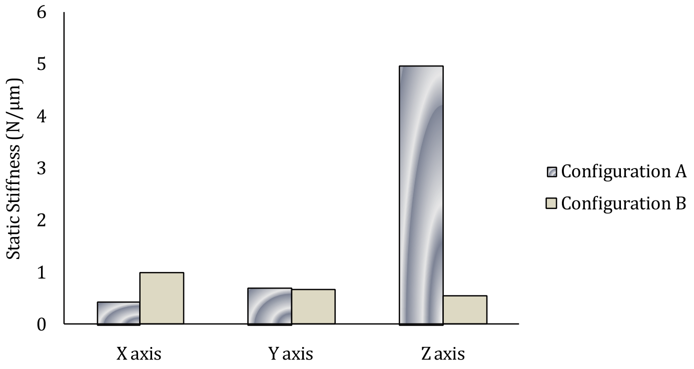

Fig. 4 Static stiffness of the tool tip for both the configurations calculated from static structural analysis

the X-axis is larger for Configuration B and both are almost similar along the Y-axis. Slightly larger stiffness has been observed for Configuration A along the Y-axis. However, the stiffness along the Z-axis is significantly larger for Configuration A as compared to Configuration B. As the cutting force is acting along the Y-direction for Configuration A and the Z-direction for Configuration B, it can be stated that the static performance of Configuration A is much better than Configuration B.

4.2 Modal Analysis

In modal analysis, the natural frequencies of the machine configurations have been evaluated using the Block Lanczos mode extraction method. It is used to determine the resonant frequencies of the machine configurations with the working frequencies of the spindle. The corresponding maximum frequency of the spindle is 2333.33 Hz. Therefore, the modes of the configurations which lie within 2333.33 may create resonance with the working frequencies of the spindle. In modal analysis, the bottom of the machine bed was kept constrained. The natural frequencies of both the configurations have been plotted in Fig. 5. The minimum natural frequency for Configuration A is 273 Hz, whereas this is 281.9 Hz for Configuration B. It can be seen that Configuration A has 9 modes below or adjacent to the maximum working frequency of the spindle. However, Configuration B has 8 modes in this zone. Therefore, Configuration B shows a lesser tendency of creating resonance with the working frequencies of the spindle. However, the cutting force may change the resonant frequencies under dynamic conditions. Hence, it is better to perform harmonic response analysis for that purpose. Figures 6 and 7 represent the mode shapes for Configuration A and Configuration B, respectively.

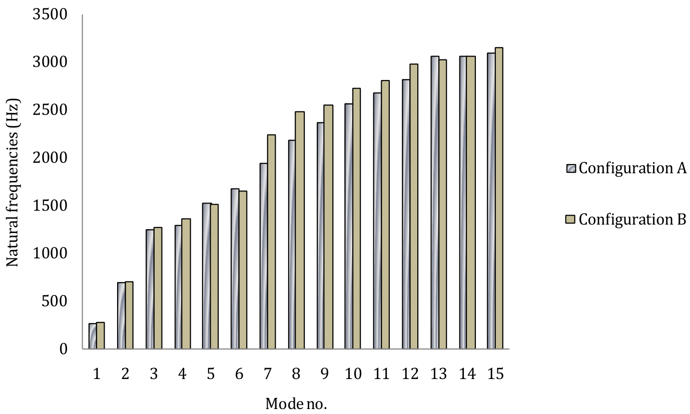

Fig. 5 Comparison of natural frequencies for both configurations determined in ANSYS modal analysis

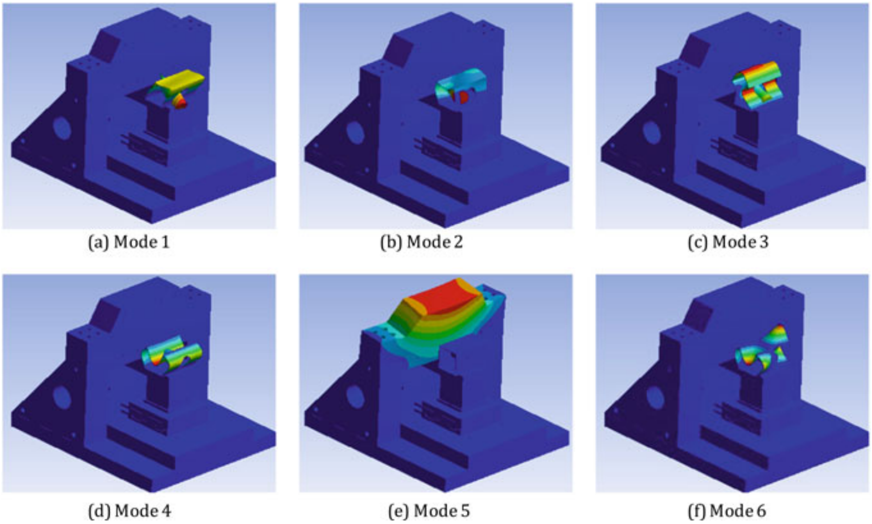

Fig. 6 Mode shapes of configuration A determined in modal analysis

4.3 Harmonic Response Analysis

Eventually, both the configurations have undergone harmonic response analysis to check the amplitude of vibration under the action of cutting force. The cutting force is harmonic in nature acting at a particular cutting frequency. In this case, the tool tip has been given a constant cutting force of 5 N along each X-, Y- and Z-directions. The cutting force has been specified based on some previous available literature. The damping ratio of the materials has been estimated from their log decrement values.

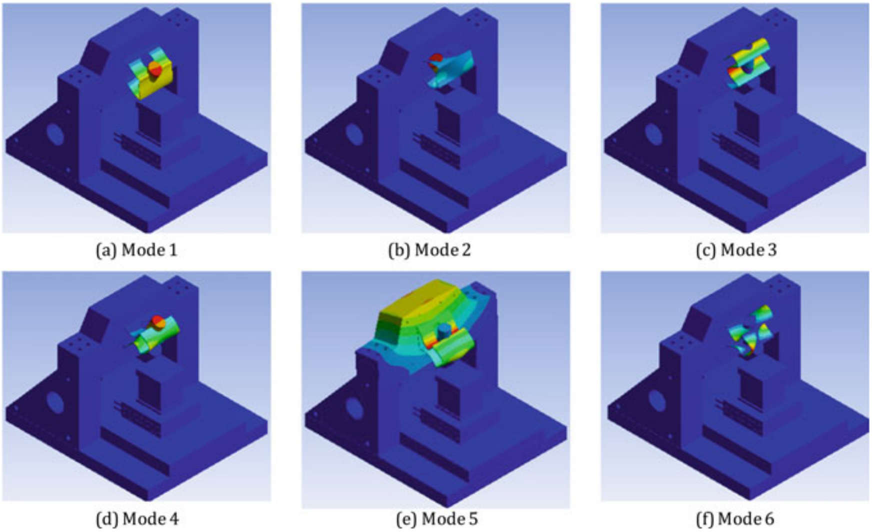

Fig. 7 Mode shapes of configuration B determined in modal analysis

Additionally, the metallic contact has possessed constant damping ratios which have been used in the analysis for the interfaces of linear stages. The amplitude of vibrations for both of the configurations along X-, Y- and Z-directions has been plotted in Fig. 8. It can be seen that the amplitude of vibration for both the configurations has been approaching toward nanometer level. However, the amplitude of vibration was larger for Configuration B along the X- and Y-axis and for Configuration A along the Z-axis. The maximum amplitudes were 24 nm, 42 nm and 55 nm along the X-, Y- and Z-axis for Configuration A. The corresponding resonant frequency was 195 Hz. Whereas, the maximum amplitudes were 45 nm, 61 nm and 47 nm along the X-, Y- and Z-axis for Configuration B. The corresponding resonant frequency was 195 Hz. The main cutting force is acting in the Y-direction for Configuration A and the Z-direction for Configuration B. However, the amplitude of Configuration A along the Y-direction is lesser compared to the amplitude of Configuration B along the Z-direction. Therefore, it can be stated that Configuration A shows better rigidity compared to Configuration B in dynamic conditions as well. It is due to the combined stiffness of the linear stages as well as the machine bed. The amplitude of vibration was reduced at higher frequencies. This is attributed to lower force transmission at elevated frequency. Additionally, the cutting force decreased at elevated spindle speed which leads to low cutting vibration in the machine tool.

Based on the performance, Configuration A shows better rigidity, stiffness and dynamic stability as compared to Configuration B. Therefore, Configuration A has been adopted for the ultra-high speed micro-milling center.

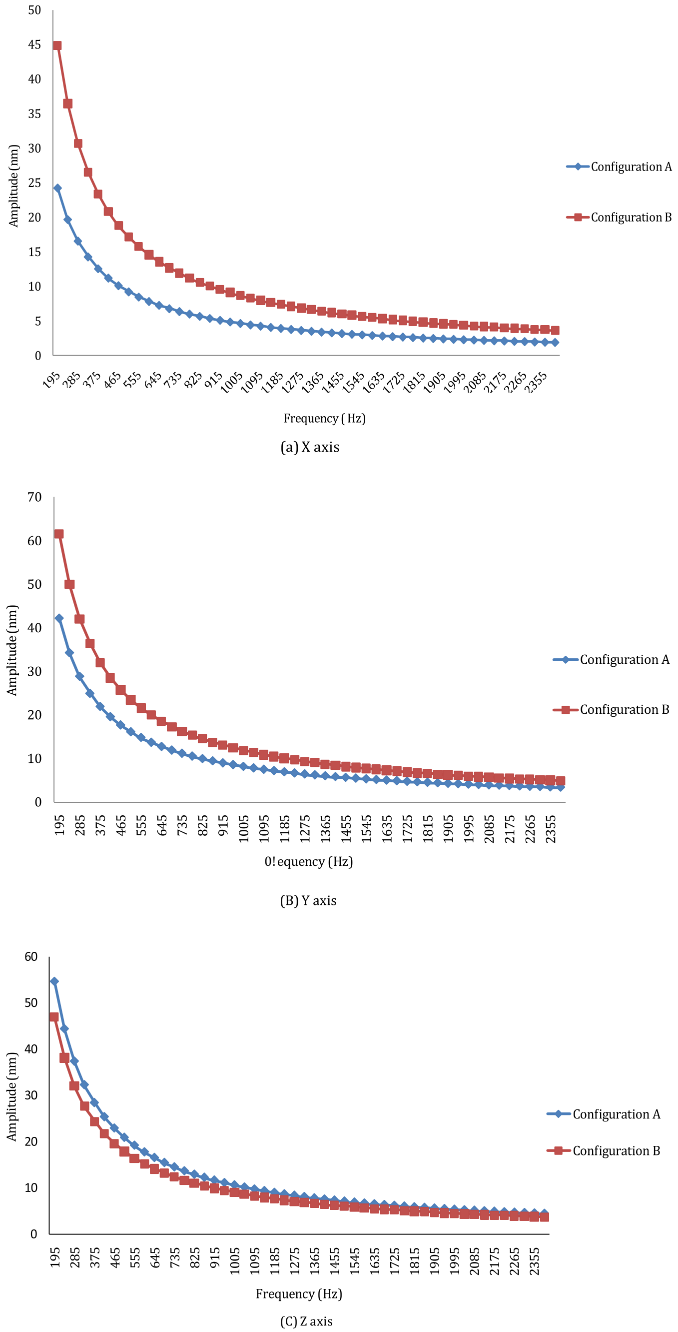

Fig. 8 Amplitude of vibration for both the configurations determined in harmonic response analysis

5 Conclusions

In this paper, two different configurations of ultra-high speed micro-milling machine tool have been discussed. The micro-milling machine consists of an ultra-high speed spindle that can rotate up to 140,000 rpm and ultra-precision linear stages. The spindle has been attached to the linear stage assembly for the first configuration (Configuration A). Moreover, the spindle was attached to the upper block of the machine structure for the second configuration (Configuration B). The purpose was to reduce the cutting vibration for the micro-milling machine. Both the configured models had undergone FE analysis to evaluate the static stiffness, natural frequencies and dynamic stability. The results show that Configuration A produces better stiffness and rigidity under both static and dynamic conditions. It is due to the combined stiffness of the linear stages as well as the machine bed. Hence, Configuration A can be used for better performance and vibration isolation for ultra-high speed micro-milling operation.

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Effect of Print Speed and Build Orientation on Tensile Strength of FDM 3D Printed PLA Specimens

P. Sowmyashree, Satya Prema, M. K. Srinivasa Murthy, and S. Raghavendra

1 Introduction

Additive Manufacturing (AM) which is also called as rapid prototyping or 3D printing is the process of creating objects by depositing material layer by layer. This is in contrast to traditional manufacturing techniques which remove extra material to get the required object shape. The process is illustrated in Fig. 1.

According to ASTM International, 2012, "Additive Layer Manufacturing" (ALM) or "Additive Manufacturing" (AM) can be defined as the "process of joining materials to make objects from 3D model data, usually layer upon layer, as opposed to subtractive manufacturing methodologies, such as traditional machining."

The workflow includes the creation of geometry using computer-aided design (CAD) tools or 3D scanners which is then converted to a STL (Standard Triangle/Tessellation Language) file format. The STL files are then imported to slicing software which breaks up the 3D model into various layers as per the user requirements and inputs which are then exported as GCODE (Geometric Code) files. The G-Code file is transferred to 3D Printer which then prints the model. The printed model is then removed from the build platform and undergoes post-processing to obtain the final part.

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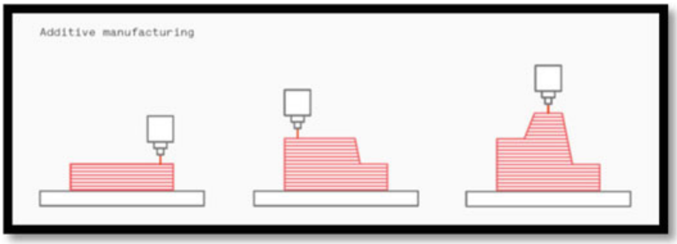


Fig. 1 Additive manufacturing process

1.1 Literature Survey

Abeykoon et al. [1] conducted a comprehensive analysis of PLA and ABS 3D printed structures varying FDM process parameters like infill density, infill pattern, infill speed and with different materials. The optimum printing temperature and infill speed were found to be 215° C and 90 mm/s for pure PLA filament based on the thermal, mechanical and morphological properties studied using experimental techniques.

Afrose et al. [2] investigated the tensile properties of PLA thermoplastic material in different build orientations processed by Cube-2 3D printer. The results showed that build orientation has a great influence on tensile properties and parts were found to be stronger and more robust printed in X-build orientation.

Nhu Tran [4] examined the impact of printing orientation on the tensile properties of parts produced using FDM technology. The study included experimental tensile tests, computational simulation and analytical calculations. The experimental result shows that specimens printed in an upright position have the lowest strength among all specimens. The difference in tensile strength between the other two orientations is slightly small. It was also observed that a considerable enhancement in tensile strength can be achieved at 95% infill density.

2 Methodology

2.1 CAD Model

As per ASTM D638 standards, a dog-bone-shaped tensile specimen is created using Solid Works as shown in Fig. 2. The dimensions of the specimen are selected on the basis of 3D printer bed size limitation and to ensure a perfect fit in UTM. The selected dimensions are length of 165 mm, width of 19 mm and a thickness of 5 mm.

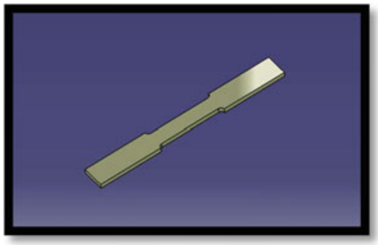


Fig. 2 Dog-bone-shaped tensile specimen

Table 1 Print time and material consumption of PLA tensile specimens

Orientation	Print speed (mm/s)				
	20	30	40	50	60
Flat (XY)	9 h 45 min 15 g (A1)	6 h 32 min 15 g (B1)	4 h 55 min 15 g (C1)	3 h 57 min 15 g (D1)	3 h 19 min 15 g (E1)
On edge (YZ)	8 h 57 min 15 g (A2)	6 h 6 min 15 g (B2)	4 h 41 min 15 g (C2)	3 h 51 min 15 g (D2)	3 h 17 min 15 g (E2)
Upright (XZ)	8 h 37 min 14 g (A3)	5 h 54 min 14 g (B3)	4 h 33 min 14 g (C3)	3 h 45 min 14 g (D3)	3 h 16 min 14 g (E3)

2.2 Rapid Prototyping of Specimens

The CAD model prepared is then imported into the slicing software Ultimaker Cura. Three build orientations namely flat (XY), upright (XZ) and on-edge (YZ) and five print speeds namely 20, 30, 40, 50 and 60 mm/s are considered for the study. The print time and material consumption for the selected parameters as well as their naming are shown in Table 1. These models are then sliced to generate specific G-Codes which are then fed to the FDM 3D Printer.

Dexbot FDM 3D printer as shown in Fig. 3a is used for prototyping the tensile specimens, and the process of printing is illustrated in Fig. 3b. The specifications of Dexbot 3D printer are shown in Table 2.

2.3 Tensile Test

Tensile testing is generally carried out for material selection for any operation, quality control and to model the behavior of the material under natural forces. During testing, a measured tension is applied to the test sample and material behavior is ecorded before the failure (Fig. 4 and Table 3).

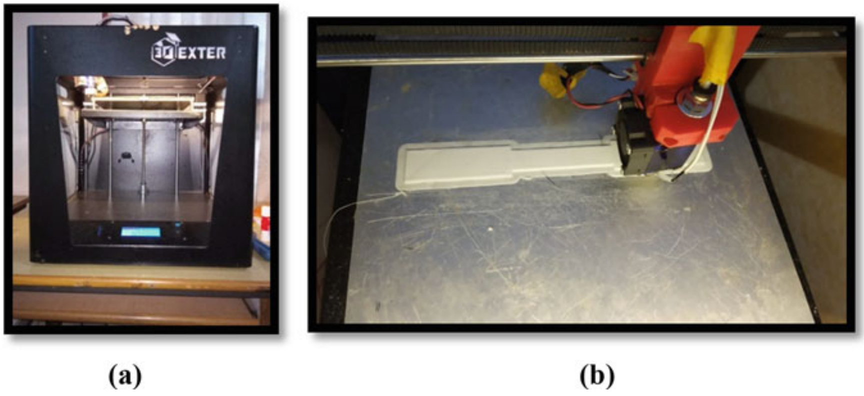


Fig. 3 **a** Dexbot FDM 3D printer Fig. 3 and **b** Printing of PLA tensile specimens

Table 2 Specifications of dexbot FDM 3D printer

Bed size	200 × 200 × 200 mm^3
Nozzle temperature	260 °C
Bed temperature	Up to 90 °C
Nozzle size	0.4 mm
Filament diameter	1.75 mm
Layer resolution	60 to 310 microns
Number of extruders	1
Material compatibility	PLA, PLA+, ABS, ABS+, PETG, Wood fill PLA, Carbon Fiber PLA, Marble PLA and Carbon Fiber PETG

3 Results and Discussion

The tensile strength and compression strength of materials can be tested using a universal testing machine (UTM), also known as a universal testing machine, material testing machine or material test frame.

The loads on a component with a force are applied. This force can be focused pressure and stress in many shapes. The concept for a load-controlled analysis is that the load varies gradually as the results of the displacement rely upon the rigidity of the structure. The 3D printed PLA specimens are subjected to tensile testing using a Universal Testing Machine (UTM) with a crosshead testing rate of 5 mm/min. The test results would be displayed as shown in Fig. 5 when the specimen is subjected to a tensile load. At least five samples were tested for each specimen to obtain more precise results. The important mechanical characteristics and their values for specimen A1 are tabulated in Table 4 (Figs. 6, 7, 8 and 9).

The above figures show the graph of comparison between loads versus. displacement (a) and stress versus strain (b) for the various test specimens which were printed

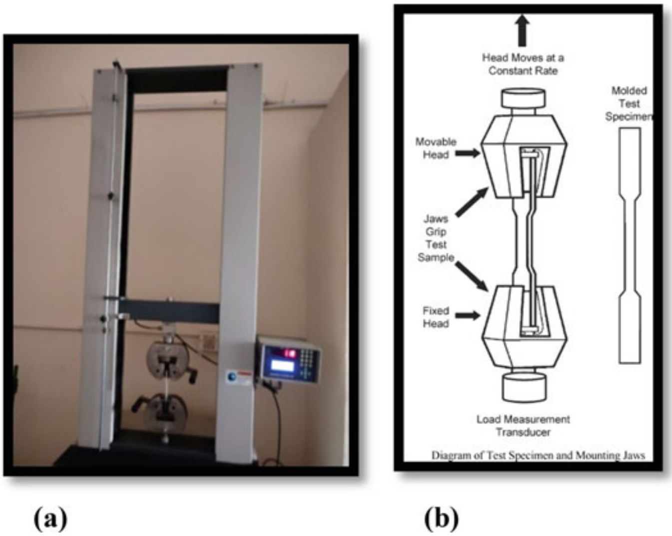


Fig. 4 **a** Universal tensile testing machine used for the study and **b** Diagram of test specimen and mounting arrangement

Table 3 UTM specifications

Model	AE-UTM-HMC-5
Reference standards	ASTM, ISO, IS
Software	AE—embedded
Horizontal day light	400 mm
Cross Travel	1000 mm
Resolution of displacement	0.01 mm
Speed	2–500 mm/min
Machine capacity	Up to 3,000 kg
Supply	230 VAC/50 Hz
Power	2.0 KW
Paint	Powder coated

in the same orientations (Flat) but different print speeds. It was found that specimen C1 had a maximum load value, whereas the maximum elongation was found in specimen B1.

The tensile strength at break load of A1 specimen, i.e., 56.67 N/mm^2 is comparable to that of properties of injection grade PLA [9] whose value is 55 N/mm^2 which serves as a validation for the present readings.

The following chart shows the tensile strength against Print speed, and the result shows a maximum value of 56.67 N/mm^2 at 20 mm/s print speed. The last chart (Fig. 10) shows the comparison between ultimate modulus and secant modulus under

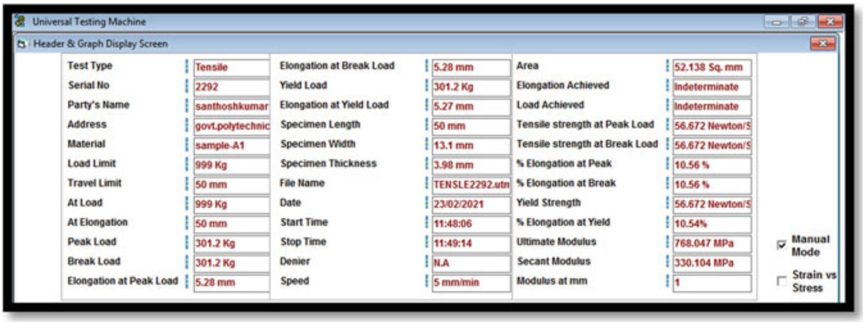


Fig. 5 UTM test results screen of a sample printed in flat orientation with 20 mm/s print speed

Table 4 Mechanical Properties for specimens A1 to E1, i.e., constant flat orientation and varying print speeds

	A1	B1	C1	D1	E1
Peak load	301.2 kg	259.7 kg	290.1 kg	285 kg	278.3 kg
Break load	301.2 kg	3.3 kg	278.8 kg	278.8 kg	273.8 kg
Yield load	301.2 kg	259.7 kg	290.1 kg	285 kg	278.3 kg
Elongation at peak load	5.28 mm	7.63 mm	5.4 mm	5.37 mm	5.19 mm
Elongation at break load	5.28 mm	9.29 mm	5.86 mm	5.56 mm	5.42 mm
Elongation at yield load	5.27 mm	7.56 mm	5.36 mm	5.32 mm	5.15 mm
% Elongation at peak	10.56%	15.26%	10.8%	10.74%	10.38%
% Elongation at break	10.56%	18.58%	11.72%	11.12%	10.84%
% Elongation at yield	10.54%	15.12%	10.72%	10.64%	10.3%
Tensile strength at peak load	56.67 N/mm^2	48.86 N/mm^2	54.58 N/mm^2	53.62 N/mm^2	52.36 N/mm^2
Tensile strength at break load	56.67 N/mm^2	0.62 N/mm^2	52.46 N/mm^2	52.46 N/mm^2	51.52 N/mm^2
Yield strength	56.67 N/mm^2	48.86 N/mm^2	54.58 N/mm^2	53.62 N/mm^2	52.36 N/mm^2
Ultimate modulus	768.1 MPa	577.71 MPa	721.02 MPa	705.35 MPa	725.5 MPa
Secant modulus	330.1 MPa	180.19 MPa	351.33 MPa	330.78 MPa	308.94 MPa

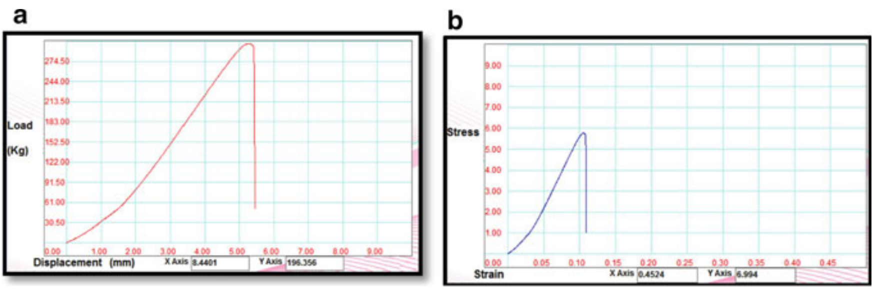


Fig. 6 **a** Load versus displacement graph and **b** Stress versus strain curve for A1 specimen

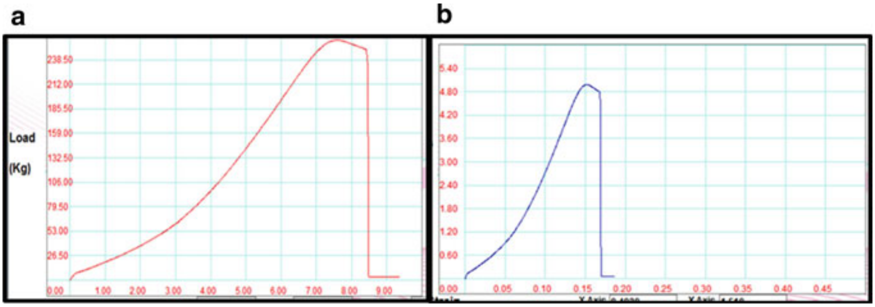


Fig. 7 **a** Load versus displacement graph and **b** Stress versus strain curve for B1 specimen

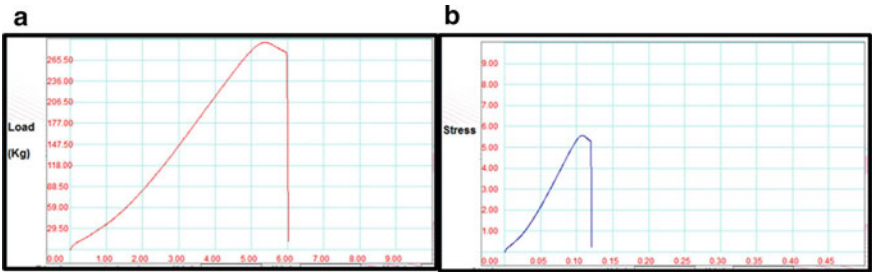


Fig. 8 **a** Load versus displacement graph and **b** Stress versus strain curve for C1 specimen

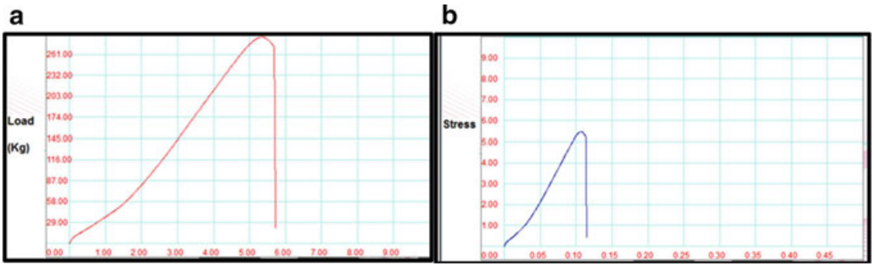


Fig. 9 **a** Load versus displacement graph and **b** Stress versus strain curve for D1 specimen

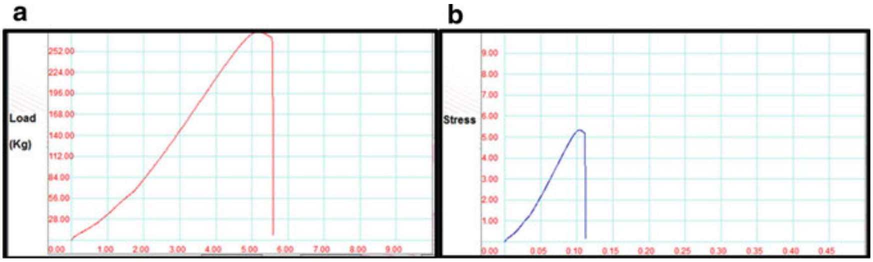
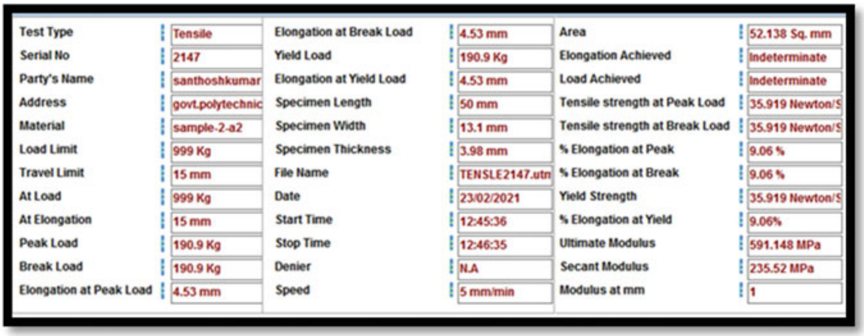


Fig. 10 **a** Load versus displacement graph and **b** Stress versus strain curve for E1 specimen

various print speeds, and both have a maximum value of 768 and 351 MPa in print speeds of 20 mm/s and 40 mm/s, respectively (Figs. 11, 12, 13 and 14, Table 5).

The above figures show the graph of comparison between Load versus Displacement (a) and Stress versus strain (b) for the various test specimens which were printed in the same orientations (On the edge) but different print speeds. It was found that



Test Type	Tensile	Elongation at Break Load	4.53 mm	Area	52.138 Sq. mm
Serial No	2147	Yield Load	190.9 Kg	Elongation Achieved	Indeterminate
Party's Name	santhoshkumar	Elongation at Yield Load	4.53 mm	Load Achieved	Indeterminate
Address	govt.polytechnic	Specimen Length	50 mm	Tensile strength at Peak Load	35.919 Newton/S
Material	sample-2-a2	Specimen Width	13.1 mm	Tensile strength at Break Load	35.919 Newton/S
Load Limit	999 Kg	Specimen Thickness	3.98 mm	% Elongation at Peak	9.06 %
Travel Limit	15 mm	File Name	TENSLE2147.utn	% Elongation at Break	9.06 %
At Load	999 Kg	Date	23/02/2021	Yield Strength	35.919 Newton/S
At Elongation	15 mm	Start Time	12:45:36	% Elongation at Yield	9.06%
Peak Load	190.9 Kg	Stop Time	12:46:35	Ultimate Modulus	591.148 MPa
Break Load	190.9 Kg	Denier	N.A	Secant Modulus	235.52 MPa
Elongation at Peak Load	4.53 mm	Speed	5 mm/min	Modulus at mm	1

Fig. 11 UTM test results screen of a sample printed in the edge orientation with 20 mm/s print speed

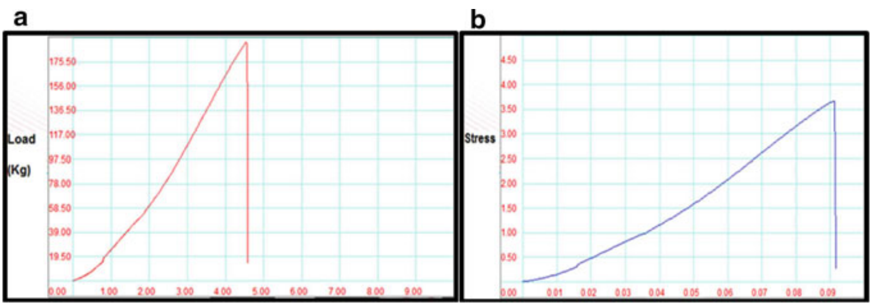


Fig. 12 **a** Load versus displacement graph and **b** Stress versus strain curve for A2 specimen

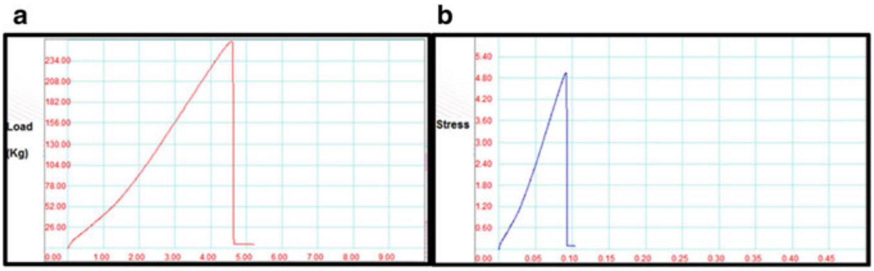


Fig. 13 **a** Load versus displacement graph and **b** Stress versus strain curve for B2 specimen

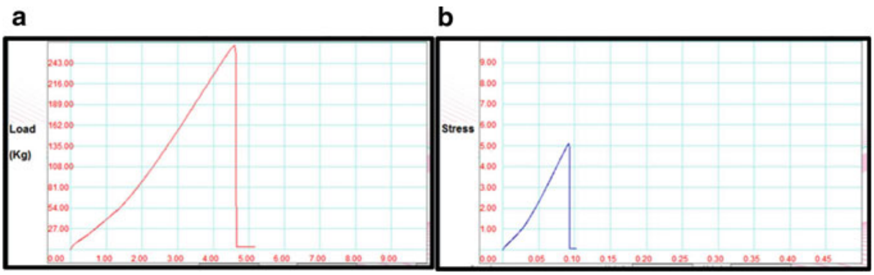


Fig. 14 **a** Load versus displacement graph and **b** Stress versus strain curve for C2 specimen

specimen E2 had maximum load value, whereas the maximum elongation was found in specimen D2 (Figs. 15 and 16).

Thus, while comparing the above data, it was found that maximum load is attained while printing at higher print speeds whereas maximum elongation is found in specimens printed in the flat position. Also, it was noted that there is a significant change in tensile strength properties as the print orientation is changed.

4 Summary

Additive Manufacturing is said to be the major driving force for the next industrial revolution. It is providing an alternative to the existing traditional manufacturing technologies. Though it has many advantages, it has its limitations due to the compatible materials and part behavior. The present study focuses on the experimental investigation of tensile properties of PLA specimens fabricated using a FDM 3D printer. The aim is to examine the influence of build orientation and print speed on the tensile strength of 3D printed parts. The results show that there is a significant change in tensile strength properties as the print orientation is changed and the optimum print speed and orientation would help in achieving the best surface finish and strength requirements.

Table 5 Mechanical properties for specimens A2 to E2, i.e., constant flat orientation and varying print speeds

	A2	B2	C2	D2	E2
Peak load	190.9 kg	258.1 kg	266.5 kg	271.9 kg	281.9 kg
Break load	190.9 kg	4.7 kg	3.5 kg	4.4 kg	281.9 kg
Yield load	190.9 kg	258.1 kg	266.5 kg	271.9 kg	281.9 kg
Elongation at peak load	4.53 mm	4.59 mm	4.6 mm	4.79 mm	4.73 mm
Elongation at break load	4.53 mm	5.07 mm	5.05 mm	5.25 mm	4.72 mm
Elongation at yield load	4.53 mm	4.59 mm	4.6 mm	4.79 mm	4.72 mm
% Elongation at peak	9.06%	9.18%	9.2%	9.58%	9.46%
% Elongation at break	9.06%	10.14%	10.1%	10.5%	9.44%
% Elongation at yield	9.06%	9.18%	9.2%	9.58%	9.44%
Tensile strength at peak load	35.92 N/mm^2	48.56 N/mm^2	50.14 N/mm^2	51.16 N/mm^2	53.04 N/mm^2
Tensile strength at break load	35.92 N/mm^2	0.88 N/mm^2	0.66 N/mm^2	0.83 N/mm^2	53.04 N/mm^2
Yield strength	35.92 N/mm^2	48.56 N/mm^2	50.14 N/mm^2	51.16 N/mm^2	53.04 N/mm^2
Ultimate modulus	591.15 MPa	712.07 MPa	736.7 MPa	752.37 MPa	738.94 MPa
Secant modulus	235.52 MPa	415.69 MPa	394.05 MPa	379.01 MPa	435.03 MPa

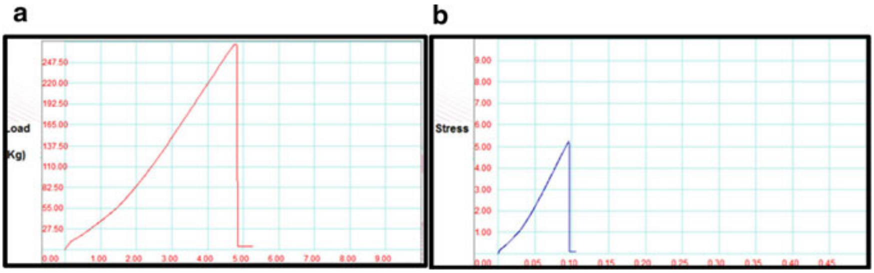


Fig. 15 **a** Load versus displacement graph and **b** Stress versus strain curve for D2 specimen

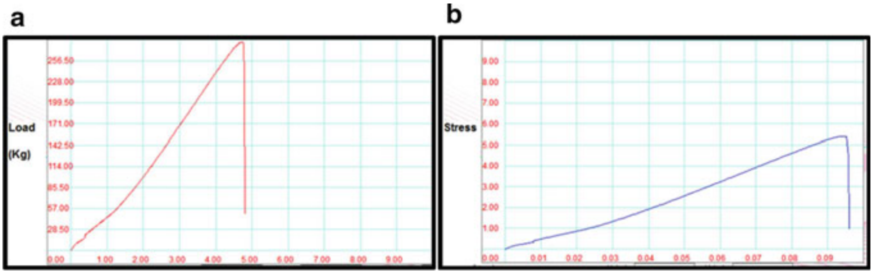


Fig. 16 **a** Load versus displacement graph and **b** Stress versus strain curve for E2 specimen

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Processing of Cementitious Materials for 3D Concrete Printing

Dhrutiman Dey, Dodda Srinivas, Biranchi Panda, and T. G. Sitharam

1 Introduction

Industry 4.0 is considered a new industrial stage in which vertical and horizontal manufacturing processes integration with information and communication technologies can help industries to achieve higher performance. Among these industries, the construction industry is regarded as the horizontal industry as it serves other industries through building infrastructure or other 'constructed assets' [1]. But it is very unfortunate to learn that the construction industry is more monopolistic in nature and always gives resistance to change for any technological innovations leading to lower productivity and higher cost [2]. Though there has been some improvement in the enterprise or company level strategies to smoothen the supply and demand side requirement, it is always lagging other sectors as there is no scientific change in the conventional construction practices [3]. In addition, the construction industry is not sustainable from economic, social, or environmental perspectives [4]. Consequently, the construction industry is shaken up by multiple global megatrends such as the affordable housing crisis (which is increasing by 2,00,000 people per day)

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and high greenhouse gas emissions (30% of the total) [1]. Considering all these facts, the building and construction industry is seen to be under a moral obligation to transform and adopt digitalization to its maximum extent. Out of all digital construction methods, the use of 3D printing in construction comes out to be a disruptive technology that starts with the digital design file (CAD) and follows a complete automated cycle to print the entire building with very little human intervention.

Concrete 3D printing (3DCP) is a novel construction method that uses the principle of additive manufacturing to build the complete structure in a layered fashion, following the 3D model. Unlike conventional construction methods, mold erection is not required in 3DCP. The application of 3DCP mainly focused on the construction sector for creating modular houses, bridges, offices, public schools, bus stops, low-cost toilet units, etc. [5]. In most of the applications, design freedom and sustainable structures are found to be the two key factors for successful implementation. Concrete printing can be divided into different groups of technologies according to the materials used and their deposition technique. In the case of cement-based material, mainly two techniques have been used so far which are (1) powder-based and (2) extrusion-based printing [6]. This method is the most frequently used one in the construction industry, which was famously known as Contour Crafting (CC) in the initial days [7]. Though this technique follows a similar deposition style used in the Fused Deposition Modeling (FDM) process, the main difference lies in the solidification mechanism of concrete material, which does not set instantaneously, rather stays in an intermediate state, leading to a challenging problem for balancing extrudability and buildability criteria [8]. However, with R&D contribution by industries and academicians, many emerging problems (material design [9], processing technology [10], Reinforcement placement [11], Mechanical and durability properties [12]) have been addressed, and by the end of 2020, a total of 29 houses have been built around the globe using 3D printing technology [13, 14]. Based on current state of the art, Fig. 1 marks the countries involved in 3DCP research and demonstration [5].

Fig. 1 Worldwide reach of 3D concrete printing in different countries

In this paper, the rheological properties of a custom-developed 3D printable cementitious mix were measured using flow table and vane shear apparatus. The influence of process parameters such as ‘print speed’ and ‘extrusion speed’ on filament shape retention and surface finish was studied using a lab-scale gantry 3D concrete printer. The mix design and process parameters were validated by printing some lattice model structures.

2 Experimental Research at IITG on 3DCP

2.1 3D Concrete Printer and Process Flow

The extrusion-based 3D concrete printing is realized through a gantry printer which is shown in Fig. 2. The most important part of this printer is the customized ‘extruder unit’; wherein the material is continuously fed into the extruder barrel, which passes through an Archimedes screw to make the concrete homogeneous during the flow [15]. In this system, the ‘print speed’ and ‘extrusion speed’ are synchronized to adjust the acceleration and speed of the printer without disturbing the material flow. More technical details of the printer can be found in Table 1.

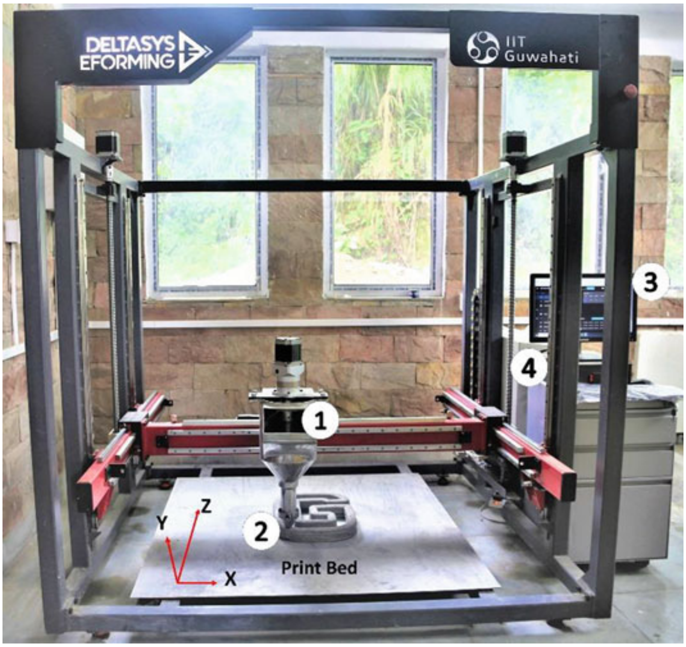

Fig. 2 Concrete 3D printer at IIT Guwahati, India (1-Extruder Unit, 2-Nozzle, 3-System for g-code generation, 4-Controller Unit)

Table 1 Specifications of customized 3D concrete printer

Technology	Gantry system
Built volume	X = 1000 mm, Y = 1000 mm, Z = 1000 mm
Print volume	X = 950 mm, Y = 1000 mm, Z = 995 mm
DOF	3
Nozzle diameter	20 mm
Nozzle travel speed	1–200 mm/s
Motion accuracy	0.1–0.5 mm (stepper motor)
Z-resolution	1 mm

The 3DCP process starts with the creation of a digital drawing file (CAD model) of the structure and then sliced in Simplify 3D, which defines the size of each layer and gives specific information about the sequence of tool path in the form of G-Codes. The controller stores the information and sends command to the printer for depositing the material in the pre-defined path [9]. The wet mix material can be continuously fed into the extruder using any mortar pump.

It is important to recognize that, there exists a strong interconnection between the material, part design, and process parameters in most of the 3D printing processes [16], but this is more pronounced in concrete printing for mainly two reasons. First is the slow curing of cementitious material, which influences the applied process parameters and print strategies such as print speed and extrusion pressure (flow rate). The second reason is assigned to the fact that concrete is a composite material and its properties are highly dependent on its composition, which plays a crucial role in controlling the printing process parameters and performance of the end product [8]. In addition to this, the design of the component or structure is also affected by the spreading of the filament during printing, the diameter/size of the nozzle as well as on some print parameters [17]. Hence, there is a need for a scientific understanding of the interconnection to get quality printing while having good control over the process.

2.2 Materials, Mix Design and Mixing Procedure

In the present study, ordinary Portland cement (OPC 43 grade) manufactured by Dalmia Cement (Bharat) Ltd, satisfying IS: 8112-2013; class F fly ash (FA) procured from NTPC Farakka, conforming to ASTM C618 [18]; and micro-silica (SF) provided by Elkem Ltd (India), having a specific gravity of 3.15, 2.05 and 2.2, respectively, were used as the binders (B). PCE-based superplasticizer (SP) in the liquid form supplied by BASF India Ltd was used as a chemical admixture. Locally available river sand (S) with a maximum particle size of 2.36 mm with specific gravity

Table 2 Mix proportions of 3D printable material

S/B	W/B	FA/B	SF/B	SP (%)
0.8	0.3	0.37	0.03	0.3

and fineness modulus of 2.65, and 2.05, respectively, was used as fine aggregate. Tap water (W) was used for all mixtures.

Many trial mixes are designed in the 3D concrete printing laboratory at Indian Institute of Technology Guwahati to optimize the mix proportion with respect to 'extrudability' and 'buildability' criteria. The final mix proportion used in this paper is shown in Table 2. Firstly, binders and sand were dry mixed at 107 rpm for a minute to obtain a homogeneous mixture using a Hobart planetary mixer. Then, around 75% of water was added and stirred at 198 rpm for 2 min. Subsequently, superplasticizer was mixed with the remaining water and added to the mixer. After that, the mixer was operated for a minute at 361 rpm to get a consistent mixture. In this study, all the experiments are done in a controlled laboratory environment (Temperature: 31 °C, Relative Humidity: 77%).

2.3 3D Printability Test Methods

2.3.1 Slump and Flowability Test

The slump cone was filled with the prepared mix in two layers, and each layer was then tamped 20 times in accordance with the ASTM C230 [19]. Excess material from the top surface was struck off using a trowel. Subsequently, the mold was slowly lifted vertically to get the reduced height as shown in Fig. 3a of the sample and noted as slump value.

The flowability of the mixture was determined using the flow table test in accordance with the ASTM C1437 [20]. After 25 blows, the diameter of the flow in two perpendicular directions was measured to get the mean diameter, as shown in Fig. 3b.

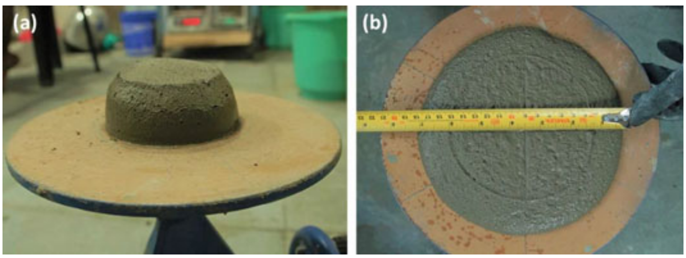

Fig. 3 **a** Slump cone test, **b** Flowability test

2.3.2 Vane Shear Test

A four-bladed (24 mm height and 12 mm diameter) vane shear apparatus generally used to measure the shear strength of soft clays was employed to measure the yield stress of the 3D printable mixture. Vane was pushed fully into the mold filled with mortar so that the top of the vane is 20 mm below the mortar surface [21]. It was then rotated at a constant rate of 0.1°/s until the sample gets failed. The maximum torque at failure was found by the difference in the initial and final reading, which was then used to measure the yield stress of the mortar sample using the equation proposed by Duzy and Boger [21].

$$T_m = \frac{\Pi D^3}{2}\left(\frac{H}{D} + \frac{1}{3}\right)\tau_y \quad (1)$$

where T_m is the maximum torque, D is the diameter of the vane, H is the height of the vane, and τ_y is the yield stress.

2.3.3 Filament Characterization

A total of fifteen filaments, each having 700 mm length were printed to study the effect of print speed on the quality of extruded filament for a given extrusion rate. To print a single layer with a height of 10 mm, three different extrusion rates (25.12, 37.68, and 50.24 ml/s) and five different print speeds (20, 40, 60, 80, and 100 mm/s) were adopted, as shown in Fig. 4.

3 Results and Discussion

From the slump and flow table test, it was found that the selected mixture has a slump of 12 mm at 0 min after mixing and flowability of 180 mm after 25 drops of the flow table. Though this mixture has a higher slump value and optimum flowability [22], it showed good buildability. This could be attributed to the faster setting and structural built-up rate of the mixture [23]. The yield stress of the material was found to be 0.44 kPa from the vane shear test. Though this value is comparatively lower for the given nozzle size to sustain higher loads coming from subsequent layers [24], this mixture was designed in such a way because, in this study, the material was only extruded instead of extrusion by pumping. From trial experiments, it was also observed that extrusion of stiff mixtures having higher yield stress becomes very difficult.

From visual inspection and measuring the width of the filaments, it was observed that low print speed and higher extrusion rates lead to the formation of wider filaments, and shark tooth patterns (as highlighted in Fig. 4) were formed on filaments

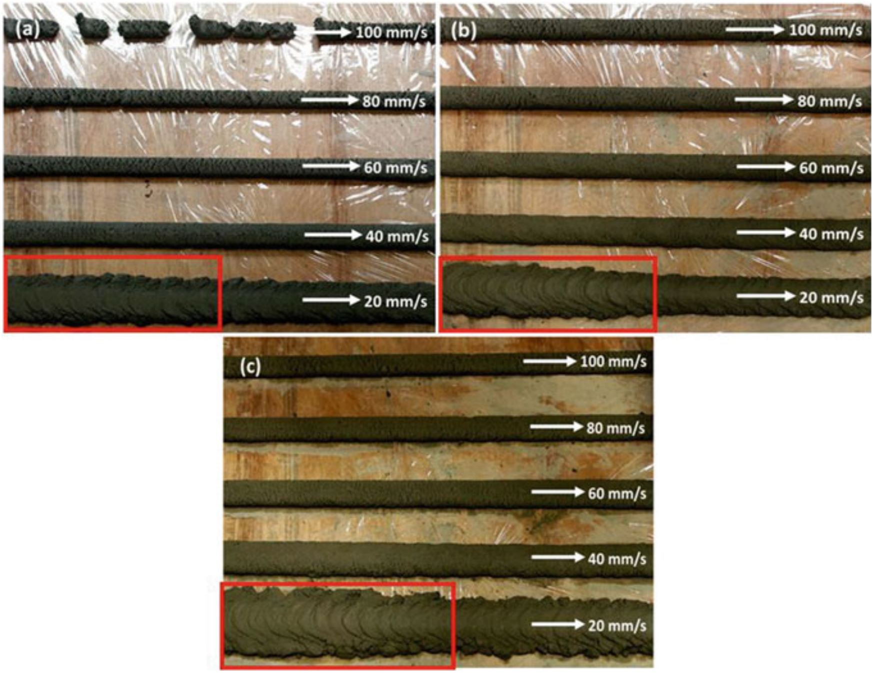

Fig. 4 Filament characterization with different extrusion rate. **a** 25.12 ml/s, **b** 37.68 ml/s, and **c** 50.24 ml/s

at very low print speed (i.e., 20 mm/s). This was attributed to the material flow in the lateral direction due to higher material extrusion than required [10]. Contrarily, filament breaks were found to be dominant at low extrusion rates (i.e., 25.12 ml/s) and corresponding higher print speeds (i.e., 80 and 100 mm/s), which was validated by printing a cylinder as shown in Fig. 5a. Though these filament breaks were not significant at both higher extrusion and print speeds, surface quality of the filament was very poor (Fig. 5b).

It was observed that increasing the extrusion rate (from 25.12 to 50.24 ml/s) produced better quality filament without any surface cracks (Fig. 5c), printed at a constant speed of 60 mm/s. This result is attributed to the rheological changes of the material, which occurs due to shearing process in the extruder.

In order to validate the developed mix for concrete printing, letters of IITG were printed up to 5 layers using the optimum processing parameters (60 mm/s and 50.24 ml/s). The letters were designed in Soildworks CAD package with dimensions of 420 mm height and 320 mm width. Figure 6 shows the 3D printed letters without any visible surface cracks and layer deformation.

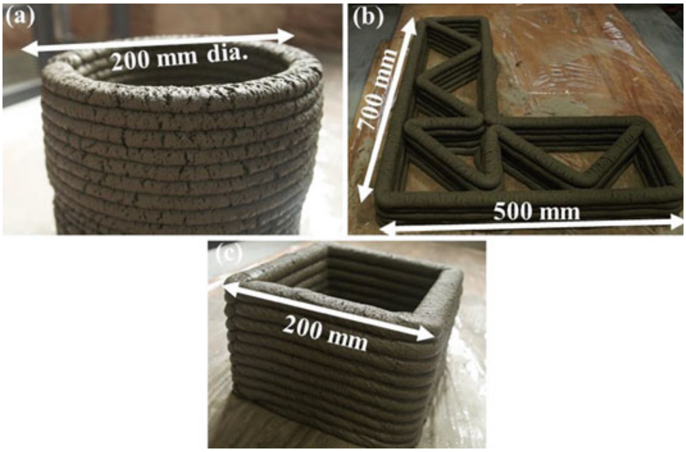

Fig. 5 3D printed lab-scale models **a** cylinder, **b** lattice wall, and **c** square structures

Fig. 6 3D concrete printed letters of IITG

4 Conclusions

In this paper, a cementitious mixture having 180 mm flowability and 0.44 kPa yield stress was used for 3D concrete printing. The material was processed in a customized gantry concrete printer, and the effects of processing parameters were investigated by varying the printing and extrusion speed. Based on the experimental finding, authors have found a set of print speed (i.e., 60 mm/s) and extrusion rate (i.e., 50.24 ml/s) for smooth, continuous filament extrusion and validated by printing the letters of IITG. It was understood from testing of other trial mixes that selection of higher or lower set of extrusion speed + print speed for obtaining a smooth filament depends on material rheological properties. Further research is needed to fully understand this effect.

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3D Printing for Fauna Research—Peeping into the Third Dimension with a Prototype Study

Guruprasad Kuppu Rao, Sagar Parekh, Rashi Gupta, Rina Dev, and Prabir G. Dastidar

1 Introduction

The research into animal species has been through observation of living, the dead, and the fossils. While the mighty dinosaurs have become long extinct, many contemporaries are seen still surviving [1]. It will be interesting to see what made a few of them cope with climate change and other hardships that made them survive to the present day. The Sea tortoise, varieties of cockroaches, and fishes have shown such tenacity [2].

This exploratory prototyping project was undertaken as a follow up of an international workshop on Social Network of Animals in Extreme Environment of Antarctica with special reference to penguins, organized by the Zoological Survey of India (ZSI), Port Blair under the sponsorship of Ministry of Earth Sciences (MoES). These primitive birds are living on earth more than 60 million years. Despite small brain, these birds show a high degree of cooperative behavior is noticed in their lifestyle. It was decided in the workshop to evaluate the brain through prototype study on a kite to assess the brain volume and in particular the front cortex.

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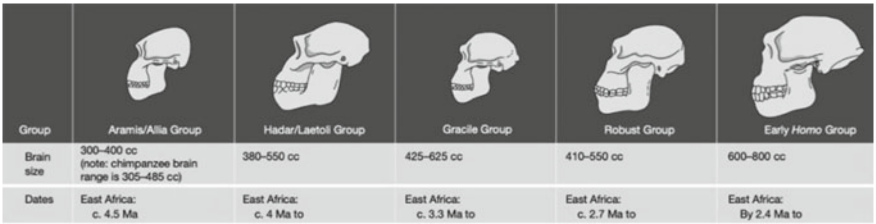

Fig. 1 Gradual increase in brain volume in Aramis to Homo group

This project was conceptualized to develop a prototyping methodology using a kite that can be further refined to apply on a deeper study on penguin brain. This will add to the data and efforts of a multidisciplinary team studying the penguin brain and aid in efforts to correlate with penguin behavior in the extreme environment of Antarctica. A literature survey on web of science database from 1982 to the present did not show any previous record of research on this topic.

Penguins, who are one of the best examples of adaptation and evolution, are seen in the coldest southern regions of the earth and are studied to know the coping skills of climate change [3, 4]. In humans, one can see Fig. 1 a steady increase of brain volume in the Aramis to early Homos group [5]. Of many aspects that are being studied, one of them being the brain volume. Birds are said to be the dinosaurs that survived and adapted to the climate change. Literature shows that brain volume hints at intelligence and better survival. The study on prehistoric fossils shows a gradual increase in brain volume [6], Andrew et al in their study [7] have shown that the Endocrinal volumes of vertebrate skulls and brain masses are often used interchangeably in comparative analyses of brain size. The concepts of brain-size/cognitive-ability relationships were first described [8] by Paul Broca (1824–1880), and Francis Galton (1822–1911)

With this and similar approaches in mind, from research partner for the feasibility of printing penguin brain and estimating its brain volume from living or a preserved dead bird carcass. A multidisciplinary team working on healthcare was in touch with a familiar veterinary clinic was pulled in for this joint project. It was planned to carry out a prototype study on a kite to ascertain the feasibility and establish a methodology.

Three-Dimensional (3D) printing has been transforming the way things are made [9]. Three-Dimensional printing is a group fabrication technology that helps us to build physical geometries from digital input data [10]. The data could be from a computer model, a scan point cloud or a medical image data [11]. Figure 2 shows the 3D printing a generic 3D printing workflow.

Due to its unique capability to make complex geometry [12], 3D printing has found many uses in medical and allied solutions. The medical image modalities such as CT and MRI capture anatomical data as a set of slice images. They can be stacked to get the volumes of anatomy (Fig. 3). These are further processed by a software to reconstruct the digital model of the target anatomy [13].

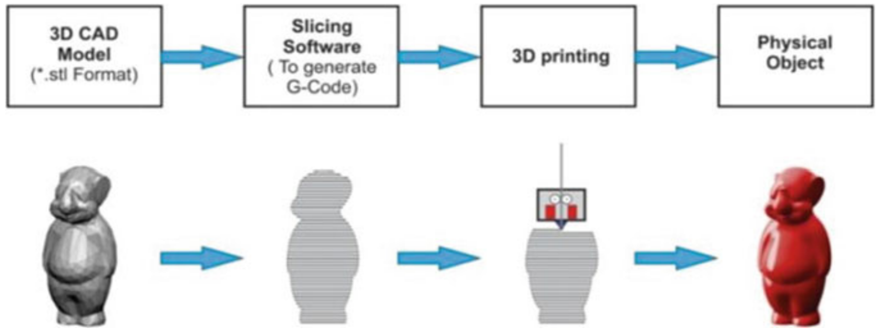

Fig. 2 3D printing workflow

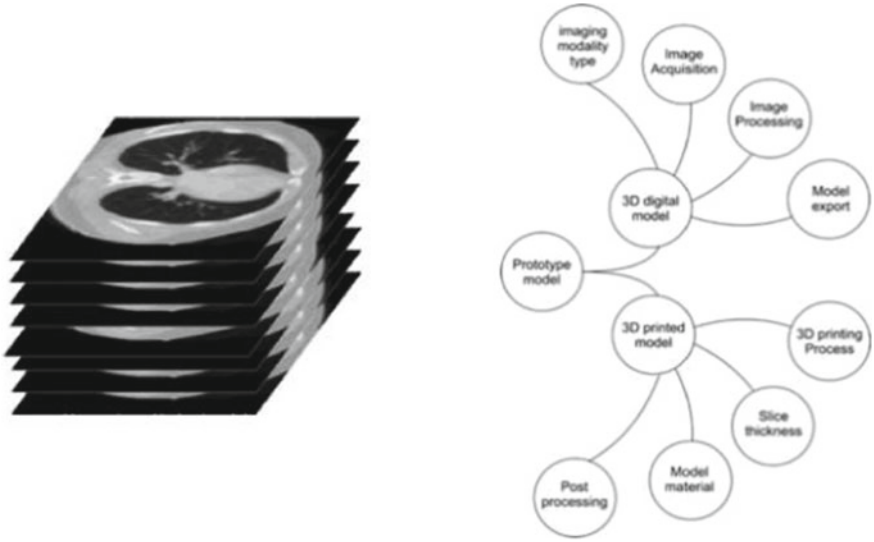

Fig. 3 Slice data to 3D model

The digital model can be used to fabricate the physical model using one of the 3D Printing processes. The Medical 3D printing applications can be broadly classified as level I–VI depending on their risk/importance Fig. 4.

There are many successful projects which improved the quality of life of a patient. Recently 3D printing is also explored for Veterinary applications [14]. We have done a few projects for birds in collaboration with local veterinary teams.

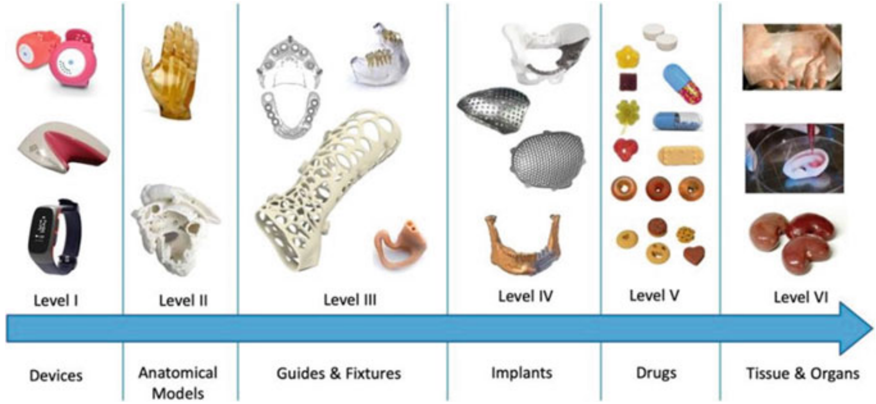

Fig. 4 3D printing application in Biomedical projects

2 Aims and Objectives

The aim of this study is to plan a prototype study on a bird to ascertain the feasibility of segmentation of its brain and hence its volume.

The objective of this research study is to establish a methodology to carry out more such studies on living or dead Penguin samples.

3 Materials and Methods

The generic Bio-sample 3D printing already established at imaginarium [15].

The steps planned are

1. Identify the Sample.
2. Prepare the Sample for CT Scan.
3. Get the DICOM dataset from CT Scan.
4. Stack the layer information to get volume.
5. Segment the target anatomy using MIMICS Software.
6. Warp the data to get a digital model of the target anatomy.
7. Get the volume in CC.
8. Export the virtual model as STL/3MF/AMF format.
9. Send the file to a 3D printer to be printed.
10. Post-processing of the 3D printed object.
11. Compare the 3D printed object and virtual model to check the reproduction quality.
12. Check both of these with CT.

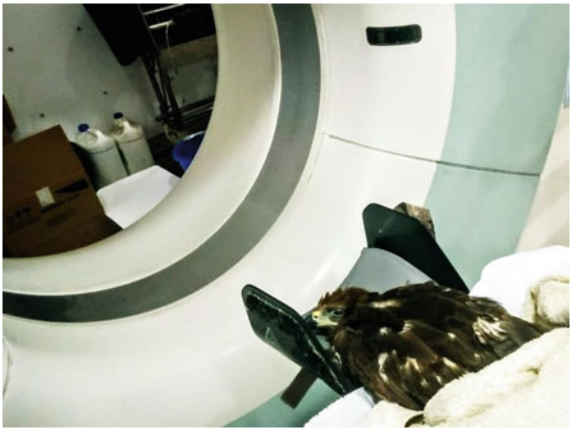

Fig. 5 The Kite is being CT scanned

13. If there are any discrepancies, the CT protocol is reviewed and improved.
14. If we arrive at a consistent dimension, we have arrived at a custom workflow.
15. The method is ready for further study on the brain.

In order to identify a suitable sample, we discussed it with the veterinarians for their advice. They get a lot of injured/sick exotic birds after being rescued by wildlife enthusiasts/forest departments. A search for a suitable bird big enough comparable to our final target sample, Penguins. A live bird was required for the CT scan. Early choice were crows or pigeons. While getting birds for a scan is difficult, finding a hospital to do the CT scan for a bird needs some persuasion. While waiting for a bird, an injured kite was brought for treatment. The bird was treated and was allowed to recover. After it was completely recovered, we decided to scan it. A regular medical imaging center accommodated and agreed to scan the bird. The bird was taken to the scan center in a pet carrier by the veterinarian with her paramedic assistant. The kite was sedated, and eyes covered to reduce its stress close to the start of scan process. The focus of scan was the head region only Fig. 5.

Post scan, we received the DICOM data from the imaging centre. The DICOM data was imported in MIMICS, the medical image processing software from Materialize NV. The data were processed with global threshold and hard tissue (bone part) and soft tissue (eye and brain) regions were further segmented (Fig. 6).

3.1 Segmentation

The segmentation not only provides sectional images but also the part volume. This will recreate a virtual 3D model. The hard tissue parts were segmented out to get only the soft tissue.

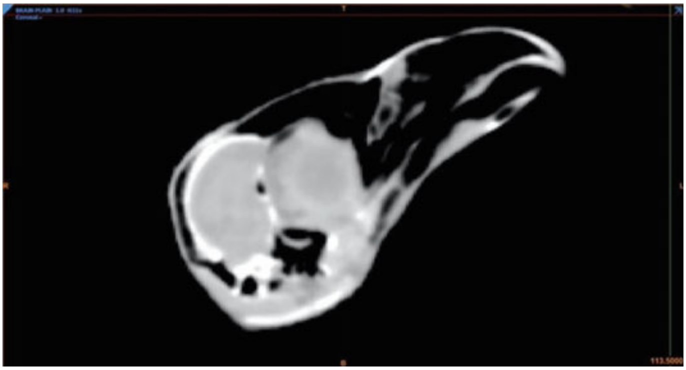

Fig. 6 Single slice of CT scan showing section

The first step in segmentation is global thresholding on DICOM dataset in which we can segregate hard tissue. This will provide the bird's skeleton with beak. It is saved as a group. Eyeballs and other non-brain tissues were also removed to arrive at the bird's brain tissue segment Figs. 7, 8, 9, and 10.

With Area of interest and region growing are used to segment out the soft tissue part to get the brain, as in part Fig. 11.

Thus, a virtual 3D volume was obtained. This virtual model can be rotated and sectioned to see the part morphology. This data can be exported into various 3D print friendly formats such as Stereolithography file (.stl), (.3MF), and (.AMF). This file can be sent to any 3D printing system to fabricate an accurate physical model of the segmented part.

In biomedical projects, usually biocompatible material is utilized to build the part. The hard part is fabricated using photopolymer resin material in the liquid form.

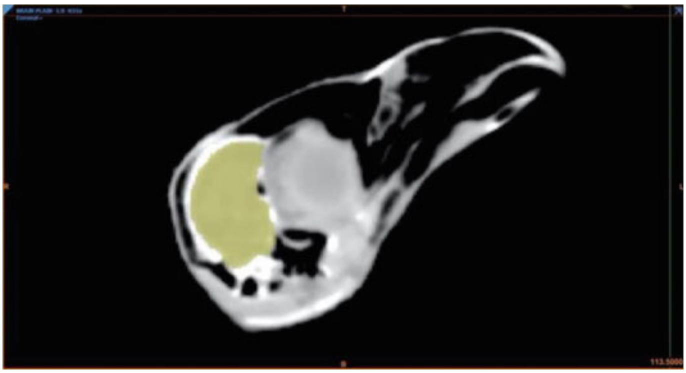

Fig. 7 Sectional segmentation of brain part

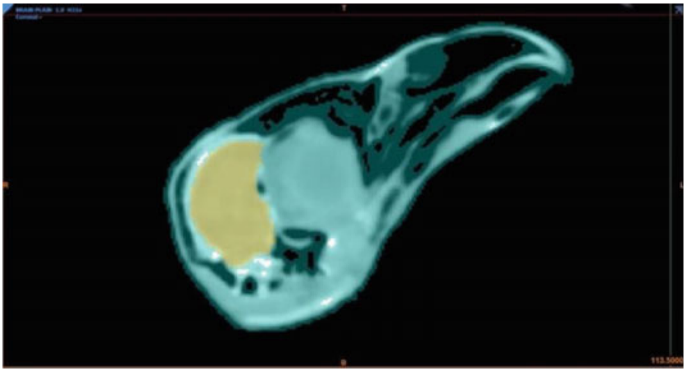

Fig. 8 Volume render of the Kite head

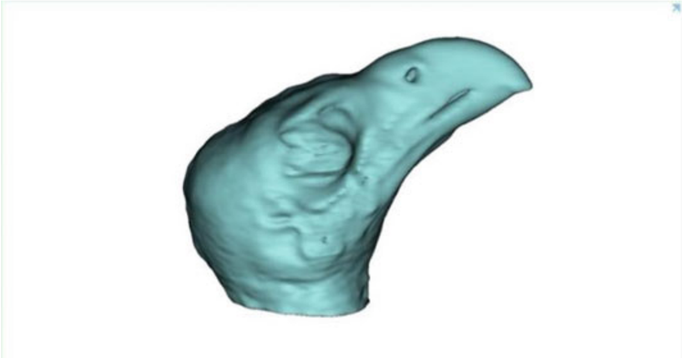

Fig. 9 Volume render of the Kite head

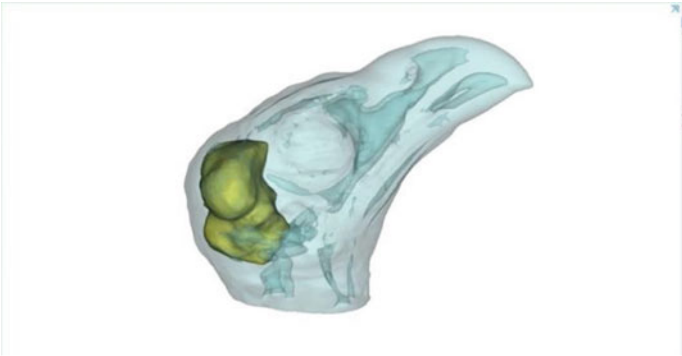

Fig. 10 Volume render with brain part highlighted rest set with some degree transparency

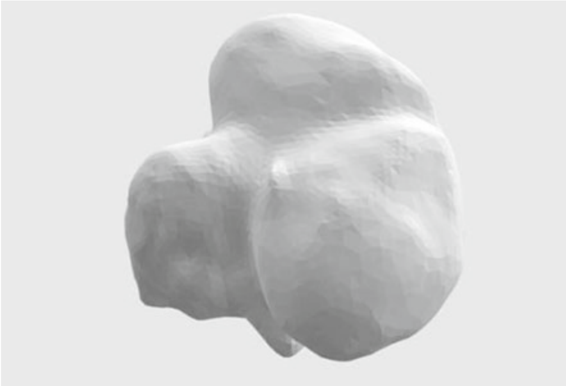

Fig. 11 Digital rendering of the segmented brain

The 3D printing method employed is Stereolithography, also called as Vat photopolymerization. This model can be autoclaved if needed. Further, the model is cleaned and measured using digital inspection tools. In the case of final project with penguin Caracas, we will compare with actual dissected anatomy.

4 Results

The target anatomy, brain of kite is successfully segmented. Figure 12 shows the segmented image.

The segmented model was evaluated with CT sections and found to be accurate.

In this project, we printed the segmented part and was measured for its accuracy. The accuracy depends on the input file, 3D printing technology employed, and the material used for printing. SLA was used with 25-μ layer thickness in Resin on a Form3 printer. The part was found to be within 50 μ.

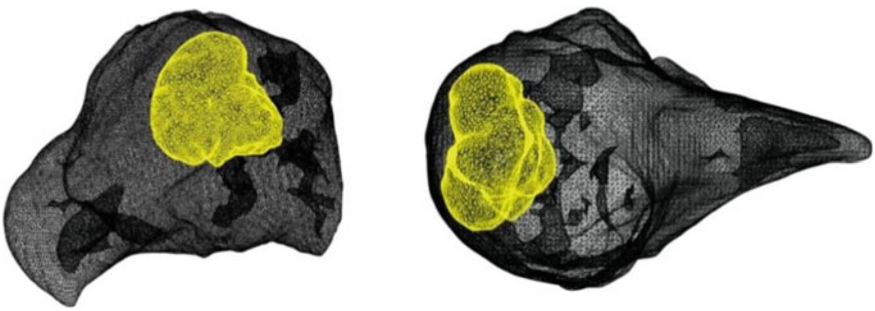

Fig. 12 STL file of the segmented brain (in yellow) showing the side & top view

5 Conclusions

The aim of this project is to develop a prototyping methodology to assess brain volume is successfully completed and has given the confidence to apply on a deeper study on Penguin Brain.

In this case the head CT of the kite, segmentation of its brain to assess volume is discussed to demonstrate the kind of inputs we can obtain for research. Teaming with the scientists, we hope to aid their study with 3D Printing to this new application and help gain insights about Penguin's brain and hence its coping strategy [16].

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Conflict of Interest None.

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Comparison of Two Different Non-coupled Multi-Step Simulation Techniques for Strength Prediction of an Electromagnetically Crimped Cu-SS Tube-To-Tube Joint with Smooth Interface

Deepak Kumar, Chinmay Morajkar, Sachin D. Kore, and Arup Nandy

Variable		SI unit
σ_y	Equivalent plastic stress	N/m^2
$\dot{\varepsilon}$ and $\dot{\varepsilon}_0$	Equivalent plastic strain rate and reference equivalent plastic strain rate	s^{-1}
A, B, C, n and m	Material constants	
T, T_r and T_m	Absolute temperature, room temperature, and melting temperature	K
c_o, c_1, c_2, c_3, c_6, c_4, c_5 and c_6	Constants of EOS	
E_o	Internal energy per unit reference volume (specific internal energy)	N/m^2
μ_c	Compression factor	

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1 Introduction

Electromagnetic crimping (EMC) is a joining by high speed-forming process, which utilises electromagnetic force or Lorentz force to induce plastic deformation in one or more parts of electrically conductive materials [1]. The process does not involve forming any metallurgical bonding between parts, unlike electromagnetic welding (EMW), and is solely based on creating an interference-fit or form-fit between the parts to be joined [2, 3]. EMC technique produces tubular joints with higher pull-out strength than the base tube [4, 5]. Some improvements in the EMC technique have also been made to enhance the joint strength further [6]. Therefore, developing an FEM model to predict the strength of an EMC joint can improve the applicability of the process. A simulation model is constructed in LS-Dyna™ discussing a smooth-surfaced EMC crimped joint along with its experimental validation having 1–4% error [5]. Various works have been done involving different types of FEM models for the electromagnetic forming process. Non-coupled models lack accuracy but are widely accepted because they ease operation and consume lower computation time [7]. However, coupled FEM models are robust and more accurate but have higher computation costs [8]. In non-coupled FEM models, the Lorentz force is separately evaluated in the electromagnetic part, and the calculated value acts as an input to compute the structural deformation of the workpiece in the mechanical model [9]. A similar methodology has been discussed using a non-coupled simulation model to study the effect of field shapers on the magnetic pressure in the electromagnetic forming process [10]. Pawar et al. have further discussed a sequential coupling model combining LS-Dyna™ and Abaqus to study the electromagnetic forming of tubes to produce mufflers [11]. Kumar et al. have used coupled FEM modelling using LS-Dyna™ to discuss various aspects of electromagnetic crimping [12]. In this study, two different multi-step non-coupled simulation models are developed to predict the pull-out strength of a Cu-SS tube-to-tube joint joined by electromagnetic crimping. Comparison of these models is also performed along with experimental validation.

2 Working Principle

In this section, joining by electromagnetic forming, also termed electromagnetic crimping, is explained using an RLC circuit. A charged capacitor is discharged, producing a damped sinusoidal current through the connected copper solenoid coil. The current produces a magnetic field that passes through the adjacent conductor/field shaper and induces a secondary current on the surface. The radial slit of the field shaper directs the current from the outer surface to the inner surface, and the current further induces another secondary current on the surface of the adjacent conductor (outer tube) that further generates another magnetic field. Interaction of opposite magnetic fields generates the Lorentz force that plastically deforms the outer tube and elastically deforms the inner tube. The difference in elastic recovery creates an interference-fit connection between the outer and inner tubes [3, 13].

3 First Non-coupled Multi-step Simulation Model

The first non-coupled multi-step simulation (Model 1) is performed in two steps using the LS-Dyna ™ software package, as shown by the flow chart in Fig. 1. The first step of the model involves a combination of the finite element method (FEM) and boundary element method (BEM) to solve the multi-physics problem of electromagnetic crimping. The combination allows studying the motion of the conductor without the necessity of remeshing the surrounding air in the simulation model. The BEM efficiently solves the Maxwell equation for regions with no eddy current. The diffusion part is solved using FEM, and the induction part is solved using BEM. The BEM technique computes the interaction between different conductors through the electromagnetic field in the air surrounding. It removes the problems of meshing

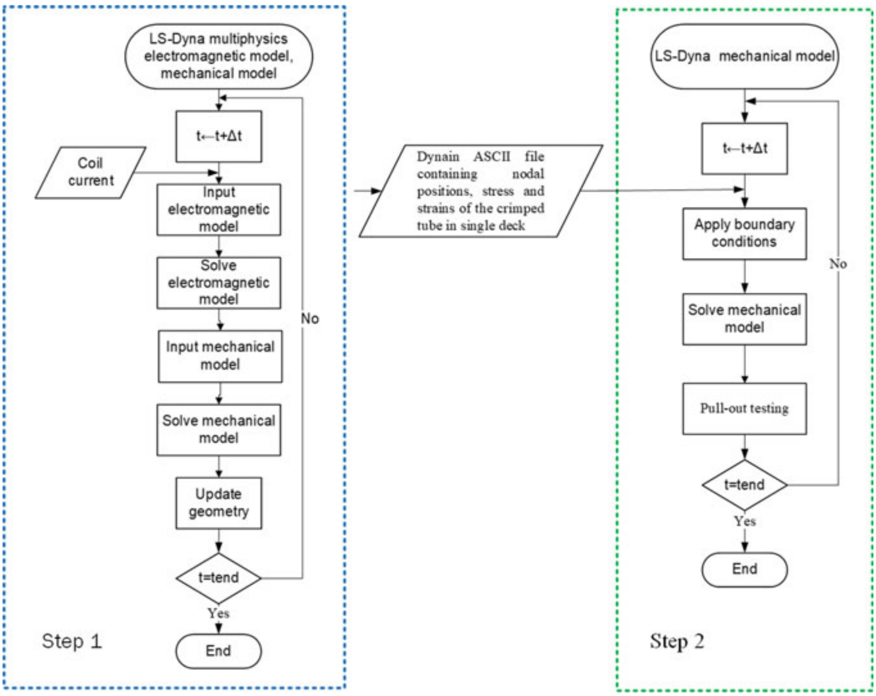

Fig. 1 Flow chart of the first non-coupled multi-step simulation (Model 1)

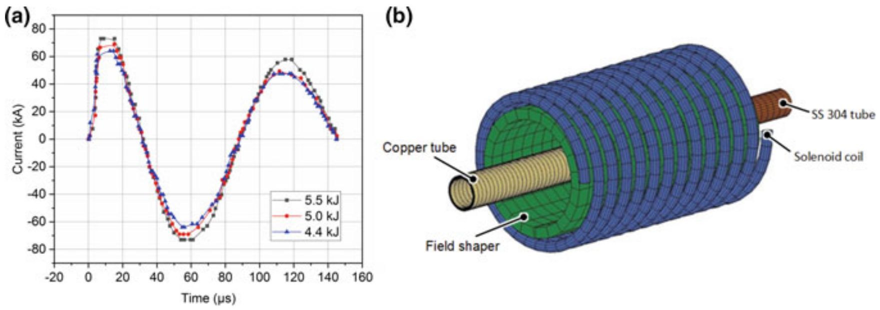

Fig. 2 **a** Current waveform flowing through the solenoid coil at three different discharge energy values and **b** meshed 3D model in the first step of model 1in LS-Dyna™

associated with the complex air region involving complicated conductor geometries. Furthermore, the BEM technique eliminates remeshing issues while using an air mesh around a moving conductor. During the first step, the magnetic field is evaluated by the electromagnetic solver to calculate the Lorentz force at each node that acts as input load to the mechanical solver at each time step which further computes the deformation of the workpiece and updates the deformed geometry in the electromagnetic solver that impacts the computation of magnetic field leading to modification of the structural deformation. This iteration continues until the end time is reached, as shown in the flow chart. The damped sinusoidal current that flows through the solenoid coil after the discharge of the capacitor bank is measured using an oscilloscope and a Rogowski coil and applied as an input load to the first step, as shown in Fig. 2a. It has been stated that the majority of the workpiece deformation occurs during the first half of the current time cycle. Therefore, only the first half of the current–time waveform is applied to the finite element model as an input load. Furthermore, these are some assumptions/conditions considered for the first step as follows: (1) The skin and proximity effects are considered during the distribution of current in the tool coil, (2) The conductance and permeability of the materials are isotropic and constant during the simulation period, (3) There is no Joule heating loss, and (4) Solenoid coil and field shaper are constrained to restrict any movement. The free ends of both tubes are constrained in all directions to replicate the nylon fixture holding the tubes during the experiment.

Dimensions of the various parts of the electromagnetic crimping setup are shown in Tables 1 and 2. Quadrilateral elements are used for meshing, and complex parts

Table 1 Working coil dimensions

Material of the solenoid coil: Cu	
No. of turns: 13	The outer diameter of the coil: 57 mm
The total length of the coil: 91 mm	The inner diameter of the coil: 47 mm
Wire diameter: 4 mm	

Table 2 Workpiece dimensions

Parts	Materials	Outer diameter (mm)	Inner diameter (mm)	Thickness (mm)
Inner tube	SS 304	10.0	6.0	2.0
Outer tube	Copper	12.7	10.9	0.9

Table 3 Material properties of the copper and SS 304

Materials	Electrical conductivity (S/m)	Relative permeability	Ultimate tensile strength (MPa)	Young's modulus (GPa)	Poisson's ratio
SS 304	1.4×10^6	1.003	505	193	0.29
Copper	59.6×10^6	0.999994	251	130	0.34

are meshed using Hyper-mesh software package and imported to LS-Dyna™ for further computation. Outer and inner tubes are modelled using eight-node linear brick elements whereas the solenoid coil and field shaper are meshed using four-node rigid elements. More delicate meshing is used for the outer and inner tubes in the area of interest (crimping zone). Simulation model showing the meshing of the parts is shown in Fig. 2b. Copper outer tube and SS 304 inner tube are used in this simulation. Material properties of copper and SS 304 tubes are shown in Table 3. The Johnson–cook (J-C) material model is used to compute the deformation of the workpiece during the electromagnetic crimping process and has been recommended for high-temperature and high-strain rate processes [14]. It can be demonstrated as follows:

$$\sigma_y = \left(A + B\varepsilon^n\right)\left(1 + Cln\left(\frac{\dot{\varepsilon}}{\dot{\varepsilon}_o}\right)\right)\left(1 - \left(\frac{T - T_r}{T_m - T_r}\right)^m\right) \tag{1}$$

Different constants and parameters of the J-C model for Cu and SS 304 are shown in Table 4. The linear polynomial equation of state (EOS) is defined in the J-C model to establish a pressure–volume relationship during the solid analysis of shock compression [14]. The equation is shown as follows:

$$P = c_o + c_1\mu_c + c_2{\mu_c}^2 + c_3{\mu_c}^3 + E_o\left(c_4 + c_5\mu_c + c_6{\mu_c}^2\right) \tag{2}$$

The constants of the equation of state are taken from the literature, as shown in Table 5. In the second step of this multi-step coupled simulation, the pull-out strength

Table 4 J-C model constants for two workpiece materials

Material	A (MPa)	B (MPa)	n	C	T_m (K)	m
SS 304	350	275	0.36	0.022	1723	1
Copper	90	292	0.31	0.025	1331	1.09

Table 5 Constants of linear polynomial EOS of copper [14]

Materials	c_o	c_1 (N/m^2)	c_2 (N/m^2)	c_3	c_4	c_5	c_6	E_o
Copper	0	140 e^9	2.8 e^9	1.96	0.47	0	0	0

of this electromagnetically crimped Cu-SS tube-to-tube joint is predicted. From the first step of the simulation that solves the Multiphysics problem of electromagnetic crimping, a Dynain ASCII file is obtained, providing the preloaded stress and strains and the new nodal locations of the crimped tubes during the first simulation. It provides information about nodes, elements, stress, and strains of the Cu-SS tube-to-tube joint involving the first simulation. This is imported into a single deck, and a pull-out test is performed. To compute the structural deformation during pull-out test, the Piecewise linear plasticity material model is implemented which is widely applicable for drop test, crash test, and different strain rate-dependent processes [15]. The boundary conditions of the simulation are according to the experimental conditions, as shown in Fig. 3. One end of the Cu-SS tube-to-tube joint has translational constraints in x-, y-, and z-directions, whereas another end has in x- and z-directions with the help of the SPC_SET keyword in the input deck. A speed of 0.5 mm/s is applied on end with no translational constraints in the y-direction with the help of the PRESCRIBED_MOTION_SET keyword.

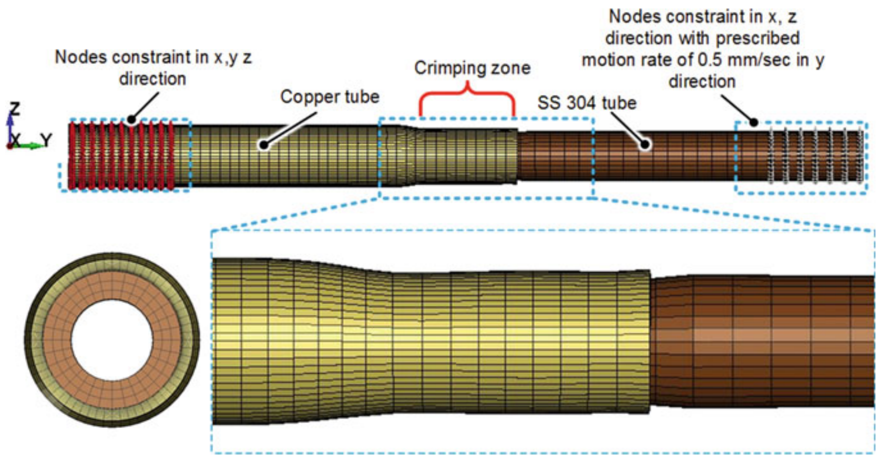

Fig. 3 Applied boundary conditions on the electromagnetically crimped joint in the LS-Dyna™ simulation model during the second step

4 Second Non-coupled Multi-step Simulation Model

The second non-coupled multi-step simulation (Model 2) is performed in two steps using two different software packages (Ansys Maxwell and Ansys Explicit dynamics), as shown in the flow chart in Fig. 4. In the first step, the electromagnetic problem is solved using the Ansys Maxwell software package. The frequency and amplitude of the first half of the damped sinusoidal current waveform flowing through the solenoid coil are measured using a Rogowski coil. The current waveform equation is obtained from it and used as an input to the Ansys Maxwell. The simulation is performed up to the first peak of the current waveform as maximum deformation occurs in the first half of the current cycle. Ansys Maxwell solves Maxwell's equation and computes the magnetic field intensity at each node and at each time step to calculate the magnetic pressure acting on the Cu outer tube in the crimping zone. The simulation has similar boundary conditions as in the first step of the first simulation model. The Ansys Maxwell 3D model is shown in Fig. 5a and b. The calculated magnetic pressure is used in the second step of the non-coupled multi-step simulation in Ansys explicit dynamics to compute the structural deformation. However, the second step is performed in two sub-steps. Crimping due to the magnetic pressure is

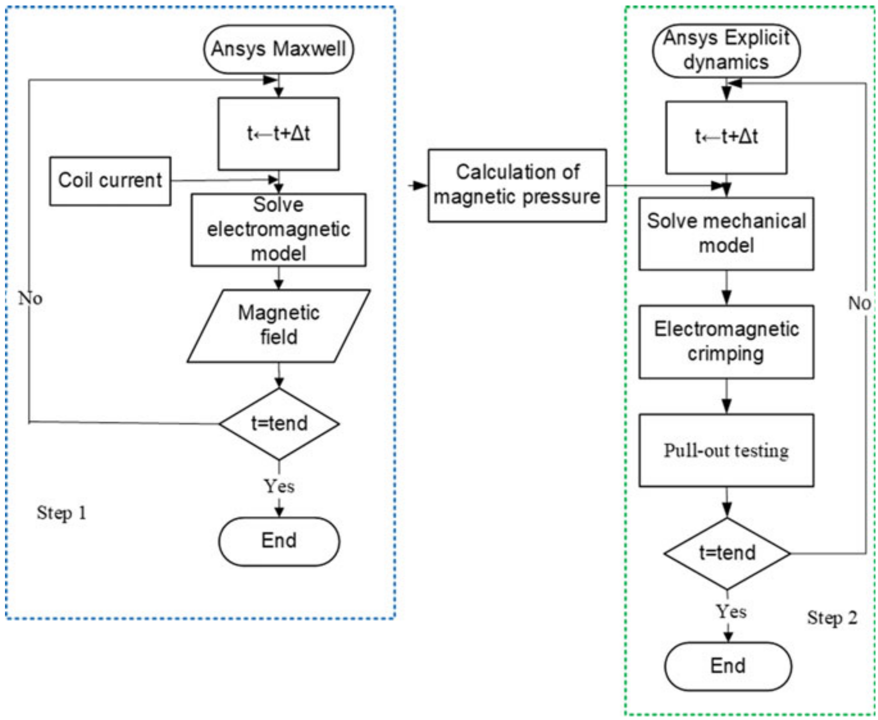

Fig. 4 Pictorial representation of flow chart of the second non-coupled multi-step model (Model 2)

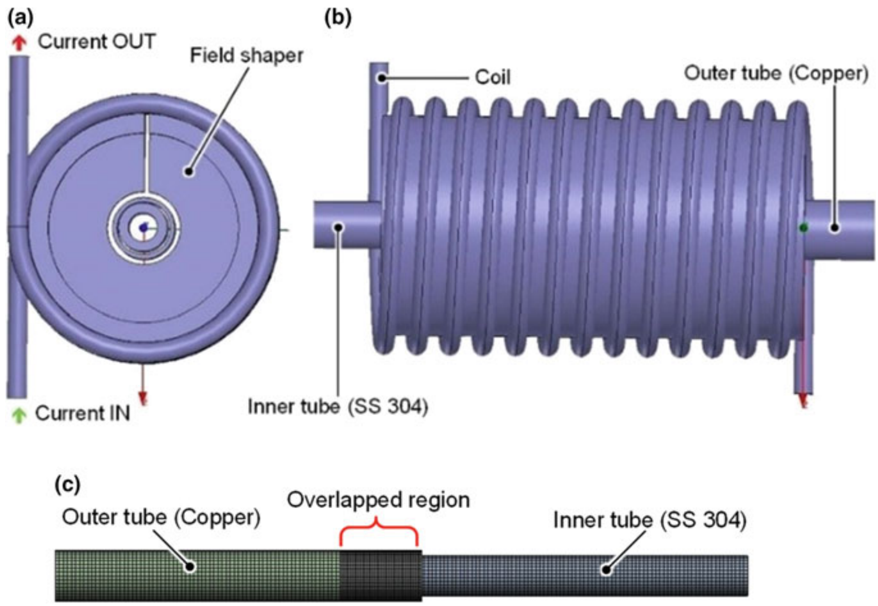

Fig. 5 3D model showing **a** Top view, **b** front view in Ansys Maxwell, and **c** final meshed version in Ansys explicit dynamics

performed in the first sub-step, and pull-out testing of the crimped Cu-SS tube-to-tube joint is performed in the second sub-step. The mechanical solver in Ansys explicit dynamics uses a transient dynamic equilibrium equation to compute deformation at each time step during the second step. The second sub-step is used to perform the pull-out test. Boundary conditions are applied as per experimental constraints. One end of the joint is applied with translational constraint in x-, y-, and z-directions, whereas a translational constraint in x- and z-direction is applied at the other end. A 0.5 mm/s of pull-out speed is applied on end in the y-direction. The meshed 3D Ansys explicit dynamics model is shown in Fig. 5c.

5 Results and Discussion

Simulations are performed for three discharge energy values (4.4 kJ, 5.0 kJ, and 5.5 kJ), and the results are validated with experimentally obtained values. Experiments are performed in two steps. In the first step, the EMC of the Cu-SS tube-to-tube joint is performed using an electromagnetic forming machine with circuit parameters shown in Table 6. Dimensions of the parts are shown in Tables 1 and 2. Polytetrafluoroethylene (PTFE) fixtures are used to place the tubes with coil and field shaper coaxially, while Kapton tape (high-temperature resistant) acts as a spacer between tubes. EMC experiments are performed at three discharge energy values (4.4, 5.0, and

Table 6 Circuit parameters for EMF machine

Capacitance (C)	Maximum voltage	Maximum energy	Circuit inductance (L)	Circuit resistance (R)	Frequency
90 μF	15 kV	10 kJ	0.7 mH	12.5 m Ω	20 kHz

5.5 kJ). In the second step, pull-out testing of electromagnetically crimped samples is performed using a universal tensile testing machine (UTM) at the pull-out rate of 0.5 mm/s. Samples are designed as per the ASTM A370 standard [16]. One end of the sample is fixed while the other end moves with constant pull-out speed. The experimental setup is shown in Fig. 6. During magnetic pressure calculation in model 1, losses due to structural deformation are considered by the LS-Dyna™. However, the losses are ignored by Maxwell in model 2. Therefore, the value of calculated magnetic pressure is higher in model 2. Experimental results after the first step are compared with the simulation results, as shown in Figs. 7 and 8. Good agreement is

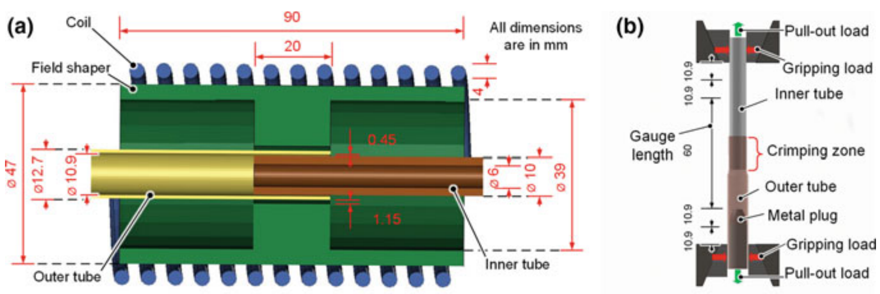

Fig. 6 **a** EMC experimental setup and **b** pull-out testing setup

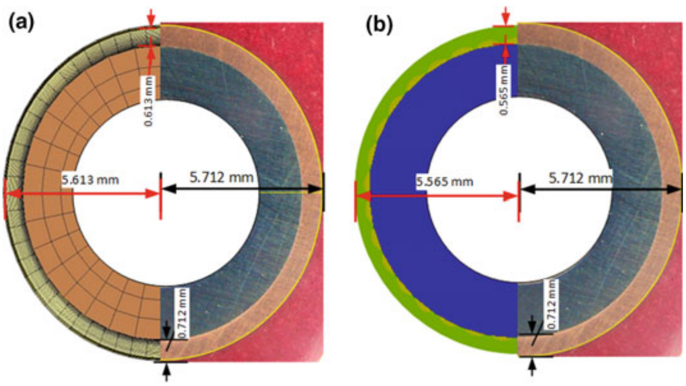

Fig. 7 Comparison of the experimentally obtained transverse cross-section of the electromagnetically crimped sample with the **a** model 1 sample and **b** model 2 sample in the crimping zone at 5.5 kJ of discharge energy (first step)

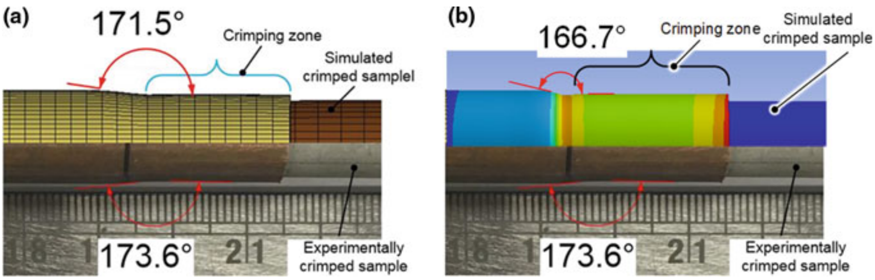

Fig. 8 Comparison of radial deformation of experimentally obtained electromagnetically crimped sampled with **a** model 1 sample and **b** model 2 sample at 5.5 kJ of discharge energy (first step)

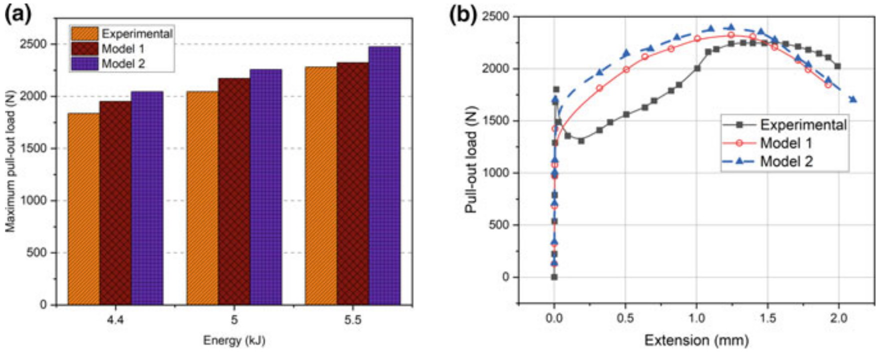

Fig. 9 Comparison of **a** maximum pull-out load at various discharge energy values and **b** pull-out load versus extension plot at 5.5 kJ of discharge energy for model 1 and model 2 along with their experimental validation (second step)

observed. The sectional view is compared by fitting half portions onto each other, and no deformation in the SS 304 tube is observed, along with an overestimation of results in model 2. Figure 9a shows the experimentally and numerically obtained pull-out data for three discharge energy values. The joint strength increases with discharge energy as higher discharge energy contributes to higher magnetic pressure, leading to higher radial deformation. That further contributes to having higher interference pressure leading to higher joint strength. Both models are in good agreement with the experimental results, with the error values ranging from 1. 81 to 6.3% and 5.1 to 10.2% for model 1 and model 2, respectively. However, an overestimation of results can be seen in model 2 due to higher magnetic pressure calculation. Pull-out load curves are also compared and shown in Fig. 9b.

The pull-out load increase with an increase in extension until it reaches the maxima and then starts decreasing. Observed maximum strength is lower than the strength of base copper outer tube, which leads to joint failure, as shown in Fig. 9b. The experimental load-extension curve initially shows a deviation from the simulation results, which is probably due to the slipping of Kapton tape during the process applied there

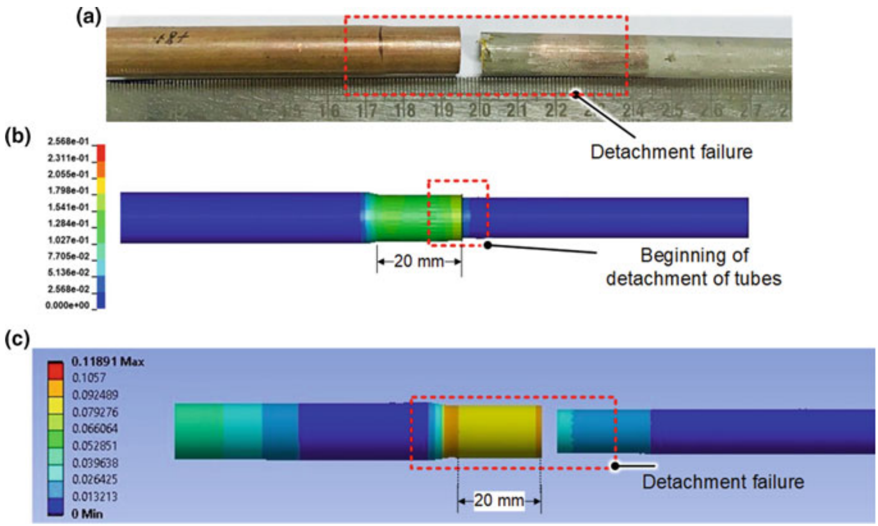

Fig. 10 Detachment failure/separation failure mode obtained during the pull-out testing (second step) in **a** experiment, **b** model 1, and **c** model 2 for samples at 5.5 kJ of discharge energy

in between tubes as a spacer. The difference between load at the initiation and maxima points is also due to the fretting and seizing effect [17]. The plastic elongation of the copper and SS 304 tube is negligible during the experiment and simulation as the joint strength is lower than the yield strength of the base copper and SS 304 tube. A relative axial movement between the outer copper tube and inner SS 304 tube is initiated during the joint failure, leading to complete separation/detachment of tubes, as shown in Fig. 10. To save computation time, the pull-out testing is performed until the relative axial movement between the tubes initiates in model 1. However, model 2 is more versatile and consumes less computation time; therefore, the simulation is performed until the complete detachment of the tube is obtained, similar to the experiment as can be seen in results in Fig. 10. Although for a smooth-surfaced Cu-SS tube-to-tube joint, detachment failure mode seems like a trivial result, if we increase the discharge energy causing the impact velocity of the outer tube exceeding the critical velocity, then the process of EMC will transition into EMW, leading to base copper tube failure mode.

6 Conclusion

Two multi-step non-coupled models have been developed to predict the pull-out strength of a Cu-SS tube-to-tube joint joined by the EMC technique, and results are compared. Computation of magnetic field is more in the case of second non-coupled model than the first one leading to higher structural deformation and overestimation of output. Cu-SS tubular joints are observed to be failed by the sliding failure mechanism. During this failure mechanism, a relative movement between the Cu and SS tubes leads to detachment of the tubes. The same has been validated from experiments. Pull-out strength values that are observed in the simulations are in good agreement with the experimental values.

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Policy and Entrepreneurship

Understanding Appropriate Teaching Pedagogy for Startup Entrepreneurship

Kumar Aashish, Krishna Dixit, and Amit Kumar Dwivedi

1 Introduction

Industry 4.0 is a collaborative network among various partners such as government agencies, research institutions, small and medium-sized firms, and startups for the development of disruptive technologies. Startups invest in innovative business products and survive in extreme uncertainty. Broadly, the definition of startup emphasizes innovativeness of business processes, innovative products/services; replicability of business process or business model; and sustainability of a newly discovered product or service. According to Kidder, startups are any original new business initiative by a founding team focused on high growth, risk-reward profile, scalability, and market leadership [1]. Startups leverage suitable technology to solve problems that have been plaguing society across sectors for a long. The most common place to initiate startup firms is the university and R&D institutions [1, 2]. It is observed that startups that come as academic or industry spin-offs have tried and solved sensitive social issues as well as business problems [1–4], which were never identified or solved by conventional businesses. Hence, it is imperative to explore the possibilities of an academic program equipped with appropriate teaching pedagogy that enables startup aspirants to venture into an entrepreneurial career.

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1.1 Evolving New-Age Start-Up Education

The conventional forms of teaching in business schools and universities are somewhat inadequate in stimulating entrepreneurial mindset among students [5]. Being interdisciplinary, the subject of entrepreneurship moved through different phases of permutation and combination of course content and learning credit until it became a well-established domain. Very recently, Potocan et al. [6] identified a set of 20 academic activities which are expected and assumed by the student community as an entrepreneurial ability buster [6]. According to Kirby [7], a formal entrepreneurship program has mainly three focus agendas: *(i) Aspiration-focused programs that enhance awareness and orientation*; *(ii) Attitude focus programs dedicated to developing competencies for entrepreneurship*; and *(iii) Ability-focused programs to harness the survival and growth of the venture.* The Growth Academy offers five modules for the startup curriculum. However, originally it had a toned-down list of three significant interventions focused on startup life stages, i.e., (i) Formation, (ii) Validation, and (iii) Scaling. This philosophy to apprehend entrepreneurship education is somehow visible as parallel to the index components of *the Global Entrepreneurship Index* [25]. The Global Entrepreneurship Index [25] has accounted Attitude, Ability, and Aspiration as major sub-index in their report, which we are also adopting in this work.

Moreover, we are adopting the guideline of SEEM framework of Startup oriented education [1] that advocates to administer fifteen different interventions at three compartments of the startup education portfolio (see Fig. 1). These three significant frameworks, i.e., GEI Sub-Index, Startup Milestone, and SEEM, are exclusively startup-oriented and much more advanced than conventional entrepreneurship frameworks.

We try to demonstrate an embedded nature of interventions for startup education in this work. By clubbing the three significant startup systems, a composite framework on which startup education will get its optimum momentum is suggested for startup pedagogy. The challenge for academicians is to synchronize the above intervention framework with suitable pedagogical inputs. While adopting a single model of startup education or a combination of world best practices is not a challenge for any academic institution, however, choosing or selecting a pedagogy that is aligned to the course objective, environment, and the kind of students in the program is the major challenge. Fortunately, the startup entrepreneurship arena has the ease to bring different stakeholders on board concerning objectivity and environment along with focused students, either undergraduate, postgraduate, or experienced professionals.

Phase-wise guidelines and contents for startup life could be framed for startup education on which suitable pedagogy can then be attached. In this paper, the segmented portfolio of pedagogical approaches developed by McCrea and Elizabeth [26] [37] is adopted. This portfolio generates four blocks, viz. Experiential and Non-Experiential; Abstract and Concrete [38]. The pedagogical tools and their combinations under these four blocks are:

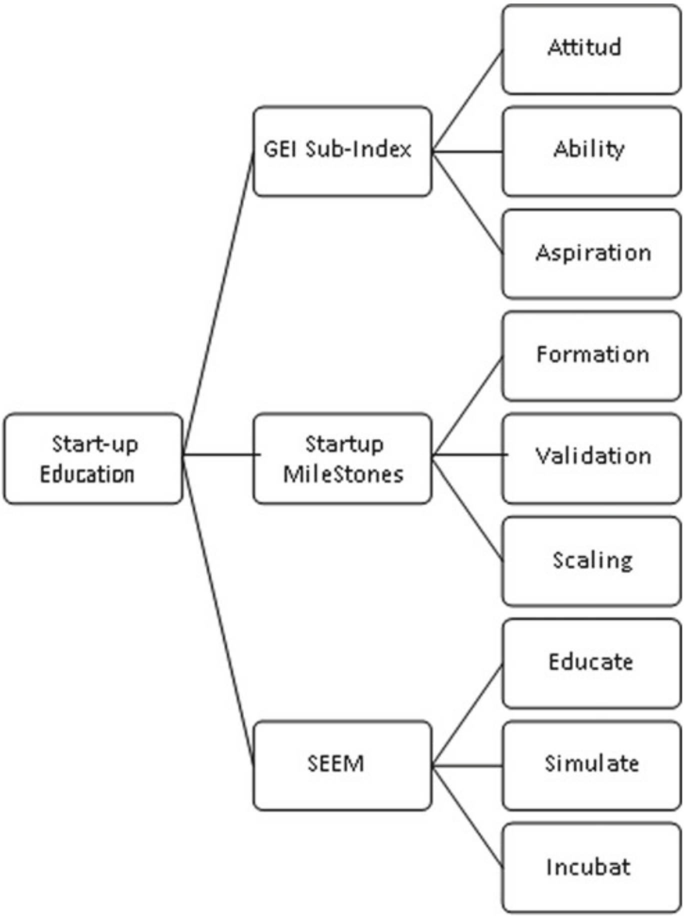

Fig. 1 GEI sub-index, startup milestone, and SEEM

a. Experiencial + Abstract = Simulation Role Playing;
b. Non-Experiencial + Abstract = Business Plans;
c. Experiencial + Concrete = Internship, Business Launch Consuting; and
d. Non - Experiencial + Concrete = Case Studies, Guest Lecture and Field Trip.

The combination of the above-mentioned approaches is backed with research and empirical practice; we posit their appropriateness to the startup era by suggesting to introduce *Ecosystem Understanding Module (EUM), Locality Startup Ecosystem Index (LSEI), and Startup Personality Map (SPM).*

1. *The* EUM does not only deal with the external business environment, but it includes students' mindsets. However, it is the responsibility of the instructor to implant entrepreneurial capital (entrepreneurial commitment * entrepreneurial

competence) among students such that they develop the capabilities to handle any situation diligently. This ability will help them not only to investigate their startup idea, but also to capitalize on the idea and make it profitable during the expansion phase. There is indeed a positive correlation between entrepreneurship education and entrepreneurship outcomes [8].

2. The LSEI is a project given to a group of students to prepare a report of the locality (City, District, or State) where they live and do critical research to evaluate startups' positive and negative factors. The EUM will help here to understand and prepare LSEI.
3. In addition to LSEI, students should be guided to prepare *their* '*Startup Personality Map (SPM).*' The SPM will include the past and present facts of the individual participant from a startup point of view. It is designed to examine personal preferences, location, lifestyle, personal history, entrepreneurial mindset and innovativeness, inclination toward technology, entrepreneurial role, and management competency required for a startup. This intervention may include computer simulation, psychometric tests, self-evaluation, peer evaluation, and mentor observation [9–14].

LSEI and SPM are the two student assessment and engagement tools that will show the impact of class interventions, discussions, and workshops. LSEI needs a peer-review model of evaluation while SPM should be analyzed and evaluated with a one-to-one discussion between mentor and participant. After formal evaluation, LSEI and SPM should be floated on social media (close group of participants or open) to get wider review comments and feedback. This will help locate participants' scope for cooperation, partnership, and the making of a strong team. The understanding of mindset and ecosystem will alleviate participants to the next level of startup understanding and decide which team is taking the idea forward because a single individual cannot fulfill every need of a startup.

2 Discussion

The focus of startup education should be to promote the formation of multidisciplinary team members. It makes the validation of ideas more scientific [44]. The approach to create multidisciplinary team formation helps to create wider pitching opportunities, results in the development of rigorous business plans, and realization of a promising prototype [3].

A rigorous ideation process is required to help students understand entrepreneurial mindset [15]. Participants of the course must have a comprehensive idea about startup, both as theory and application, and be able to align their thinking process in a way that results in idea germination. Idea generation and opportunity recognition are ideation processes that are essential in setting up and functioning a startup. Students need sufficient exposure to planned ideation intervention pedagogy [16].

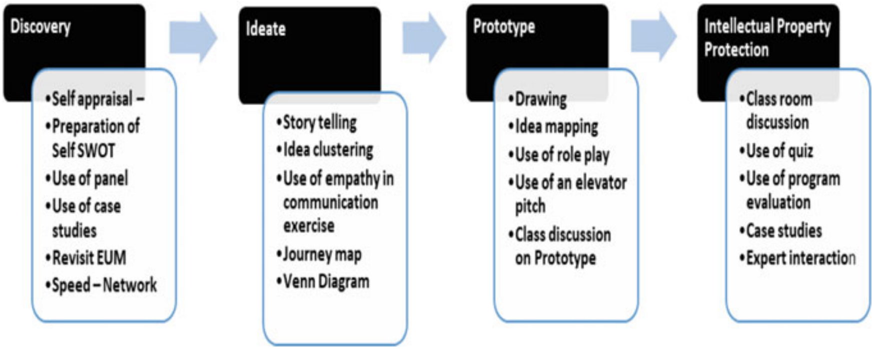

Fig. 2 Startup centric prototype approach and pedagogical interventions

Both design thinking and startup thinking undergo similar stages of transformation. Through this conceptual paper, we would like to juxtapose the startup process with the design process. The design process has three phases: discover, ideate, and prototype [17]. Authors advocate here that the foundation for any startup campus demands a planned pedagogical intervention that will help the student community to recognize and determine a workable idea and design a business model that could sustain it (Fig. 2).

Let us discuss these phases one by one:

A. The pedagogical intervention is intended to make participants open to untapped opportunities and inspire them to create innovative ideas with the right amount of preparatory homework in the initial stage. As part of this section, the instructor should help students identify and choose the type of challenges they would like to work on during startup formation. The potential learning hubs for inspiring startups are its community, experts working in the challenge area, and the business context and peers. The panel discussion, brainstorming, role-play, and workshops are the tools suggested for pedagogical intervention. The discover-phase of pedagogy provides a frame for the next phase that is ideation.

B. The ideation phase of pedagogy will help transform a discovery based on research into a startup idea. The conceptual structure evolved out of the discover-phase will help to practice brainstorming novel ideas. The pedagogical interventions stated in the above table with respect to ideation are intended to encourage startup teams to think expansively and without constraints. In the ideation phase, perspectives evolve, and the students will understand what their observations mean as a potential startup idea.

C. The pedagogical interventions related to the prototype phase prepare students to make their idea tangible, and learning, therefore, becomes a natural corollary to prototype building. Feedback from peers and the instructor further strengthens the prototype and enhances their ability to design prototypes. Intellectual property sensitization program and professional development workshop dedicated to understanding the types of IPs, case study on the disputes of IPR and contemporary issues in IPR through panel discussion, expert interaction are some of the desired pedagogical interventions [47] for effective sessions on intellectual property protection sessions in startup education.

D. The knowledge spillover theory of entrepreneurship [18] 19 propagates indigenous knowledge cultivation in academic institutions' commercialization by converting research outcomes into products and services. The university technology transfer should not be taken with a linear perspective but as a holistic approach to developing innovation-driven startups on campus with indigenous technology. It is high time to combine entrepreneurship education activities with knowledge, technology, intellectual property, and commercialization efforts to spawn into a startup campus ecosystem.

Earlier, the entrepreneurship education was more focused on business plan preparation [20–22], but the consistent higher rate of failure of enterprises across geographical context indicated that there is something wrong in the existing approach, and scholars identified the business model as precedence of the business plan [23, 24].

Keeping the advent of startups and their nature, the business model exercise does not suffice the need, and the 'Opportunity Analysis Canvas' [6] exercise should get a robust platform.

3 Conclusion and Scope for Future Research

Throughout this paper, we intend to invite the reader community to locate and visualize startup creation as an educational journey. It is expected that this paper will serve to realize the need for a teaching doctrine for startups. This paper argues that the academic ecosystem in campuses is a must to stimulate sustainable startup ideas among students. The process aims to contribute new learning verticals based on laboratory research, industry experience, and day-to-day experience as potential triggers for startup ideas.

In this work, authors have taken Global Startup Ecosystem Report [25] and Human-Centric Design Thinking (IDEO) as lamp posts to direct the students to prepare a 'Locality Startup Ecosystem Index' and derive a genuine startup idea, besides establishing the conceptual links among them. Additionally, pedagogical interventions are emphasized for the effective upbringing of student entrepreneurs. Realizing the fact that startups are heavily innovation and technology-driven, both of which are products of the human mind and need to be protected, intellectual property protection was suggested as an important component of a course on startups. Also, keeping the gaps in entrepreneurship curriculum for startup courses and lack of relevant pedagogy for startup education, an attempt was made to understand and appreciate tested and tried alternative pedagogies. Lastly, this paper advocates support and motivation-oriented startup education rather than mere drilling for skill development.

Derived from three different entrepreneurship thoughts related to each other, this paper tries to provide appropriate teaching pedagogies for startup education. However, apart from setting a framework for pedagogical intervention, the authors did not aim to put up an administrable format (syllabus or guidelines) for startup education. Creating an exhaustive list of contents and requirements for running an effective startup course remains an incomplete project yet. Drawing from the conventional entrepreneurship education framework of theories and practice, this paper attempts to address the gaps in the knowledge for technology and innovation-driven startup ventures that is typical of the twenty-first century. The elements of a conducive campus ecosystem or community ecosystem for the growth of startups with promising ideas are yet to be configured theoretically. Such theoretical advancements and scholarly ventures could help policymakers, academicians, and investors to visualize upcoming Silicon Valley and guide other research scholars working in startup education to produce intellectual insights on the subject.

There is also scope for validating this conceptual link by connecting every possible factor discussed in this paper and analyzing their interconnectedness, and studying their relationship with each other.

- *What is the role of pedagogical intervention in creating a sound campus ecosystem for startups?*
- *To what extent does startup pedagogical intervention has an impact on the startup aspirants?*
- *How competent are the suggested measures in startup pedagogy?*
- *What are the essential parameters that could help us measure the quality of a course in startups?*

These are some of the questions that scholars and educators must ponder over.

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Overview of Multi-Stakeholder Approaches and Initiatives for Achieving Sustainable Development in the Residential Sector

Kratika Piparsania and Pratul Kalita

1 Introduction

Globally, building floor space has expanded 65% since 2000, while energy/m^2 has improved by only 25% [1]. India experiences the fastest relative growth in per person residential energy use because of increased access to energy sources and increased use of appliances and other energy-using equipment. India's urban population raised from 290 million in 2001 to 378 million in 2011, and projects reached 590 million by 2030 [2]. In 2017, approx. Two hundred seventy-two million households were estimated in India, increasing to 328 and 386 million in 2027 and 2037. The residential sector floor area anticipates rising to 21.9 billion m^2 in the next ten years from 15.3 billion m^2 in 2017 [3]. Urbanization in India results in an increase in towns and cities and the rising population in urban areas. According to census 2011, 37.7% of India's 121 crore people live in urban areas, and this number is rising continuously [4].

The increasing population in urban areas requires more buildings to work, live, and interact, increasing the number of facilities, resulting in a projected rise in electricity demand. An increase of 400% in the collective floor area of existing buildings and 20 billion m2 of new building floor area is expected by 2030 [1]. However, the poor construction details and lack of energy-efficiency measures provide a high potential for energy savings, both in demand and consumption. It is necessary for India now to develop energy-efficiency strategies focused on the residential sector to limit the current trend of unsustainable increasing energy demand. The sectoral coverage of India's climate policies is diverse, and targets for climate action focus on specific areas essential for long-term, low-carbon growth. India has progressed toward N.D.C., with a decline in the emissions intensity of 21% in 2014 from 2005 levels, against the

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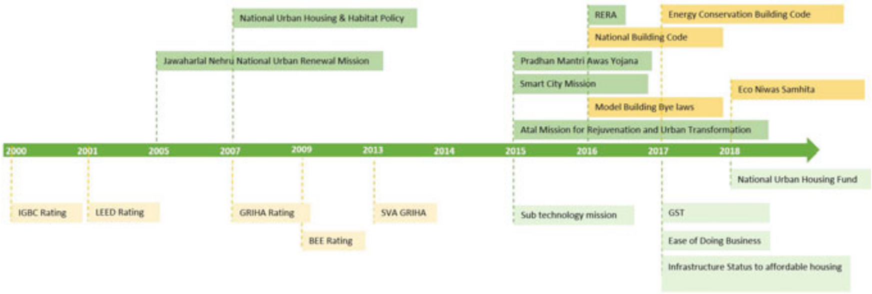

Fig. 1 Policy landscape of India. *Source* Translated by Author (MoHUA, MoP)

20–25% reduction by 2020 and 33–35% reduction by 2030 [4]. India will experience massive growth in commercial and residential building construction over the next two decades. Recognizing energy efficiency as a resource and enhancing the energy efficiency of the upcoming building stock is imperative for India's development.

2 Background

The Government of India (GoI) has been developing policies and programs to guide urban planning and energy management mainstreaming. Urban Policy, planning, and housing are state subjects according to the Constitution of India. However, the central Government has played a proactive role in housing matters by formulating policies and programs, giving directives to the state, and allocating funds under the five-year plans [5]. To meet citizens' energy needs and reduce carbon emissions, the Indian Government has adopted a two-pronged approach, i.e., focusing on supply and demand. On the generation side, greater use of renewable energy, mainly solar and wind, is being promoted. On the demand side, efforts are being made to improve energy efficiency through various innovative policy measures within the 2001 Energy Conservation Law umbrella [5] (Fig. 1).

The Government of India has three levels in its governance structure, i.e., central, state, and city levels, which are merely responsible for forming and implementing rules and regulations. The following Fig. 2 explains the roles at each level under the governance system.

3 Methodology

To understand the role of stakeholders and their contribution to sustainability, we need to comprehend their involvement and initiatives led by them. Also, it is required to understand the implementation mechanism at the grass-root level. The focus

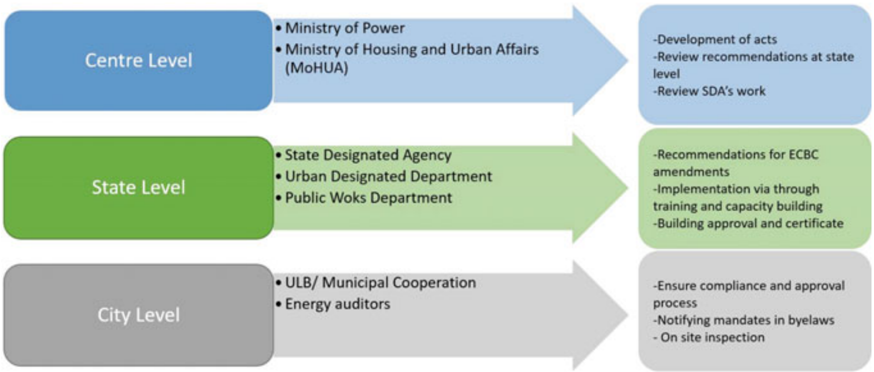

Fig. 2 Governance structure of India. *Source* Translated by Author (MoHUA, MoP)

on sustainability must generate from both supply and demand side to build new proposals.

4 Identified Stakeholders, Their Roles, and Existing Government Policies

The Ministry of Housing and Urban Affairs is entrusted with the broad policy formulation, administration, and monitoring of the various schemes relating to the nation's housing and urban development. The development of cities is a state responsibility, and the Constitution (Seventy–Fourth) Amendment Act of 1992 assigned several duties to urban municipal governments [6]. On the other hand, the Government of India coordinates and monitors numerous urban housing projects, urban livelihood missions, and overall urban development through Central and Centrally Sponsored Schemes. The Ministry promotes a wide range of urban-related challenges through practical policy guidelines, subordinate legislation, and sectoral programs [6].

The governance structure for the state has been illustrated in Fig. 3:

Fig. 3 The governance structure for the housing scenario in India. *Source* Translated by Author (MoHUA)

4.1 Policy Outlook Under Housing Sector

This section outlines the primary housing policies/schemes that have been launched by the Government of India, which formulates the housing sector.

The Ministry of housing and urban affairs announced the Jawaharlal Nehru National Urban Renewal Mission in 2005 as the first flagship scheme of this Ministry. JnNURM scheme has two components: Basic Services for Urban poor (BSUP) and Integrated Housing and Slum Development Programme (IHSDP), both intended to develop slums through housing projects [7]. The Mission was initially for seven years, i.e., up to March 2012, which was extended up to March 2014 for completion of the already approved projects. During March 2013, the Mission period was extended by one more year, i.e., up to March 2015, to complete ongoing works [7].

In 2007, the Ministry of Housing and Urban Poverty Alleviation announced the National Urban Housing & Habitat Policy, which aims to encourage various forms of public–private partnerships to achieve the objective of "Affordable Housing for All," with a focus on the urban poor. The Policy aims to encourage sustainable habitat development in the country to provide an equal supply of land, shelter, and services at affordable rates to all segments of society [8].

Pradhan Mantri Awas Yojana (Urban) is introduced by MoHUA, launched in June 2015, ensuring housing for all in urban areas, is a first-of-its-kind initiative designed to provide 'Housing for All' by the end of the year 2022. The Mission offers Central Assistance to implementing agencies via States/Union Territories (U.T.s) and Central Nodal Agencies (C.N.A.s) to provide homes to all eligible families/beneficiaries by the verified housing need [9]. The dwellings built under the Mission shall be planned and constructed to fulfill the structural safety standards of the National Building Code and other applicable Bureau of Indian Standards (BIS) norms. The houses under the Mission should be designed and constructed to meet structural safety requirements conforming to the National Building Code and other relevant Bureau of Indian Standards (BIS) codes [5].

The Government of India has established the Atal Mission for Rejuvenation and Urban Transformation (AMRUT) to improve the quality of life for all, particularly the poor and disadvantaged, by providing basic civic facilities such as water supply sewage, urban transit, and parks. Another project launched by the GoI in 2015 is the Smart City Mission, which supports sustainable and inclusive communities that offer basic infrastructure and good quality of life to their inhabitants, a clean and sustainable environment, and the use of 'Smart' Solutions [6]. The Mission will be implemented through four verticals, giving beneficiaries, U.L.B.s, and State Governments. The Government of India introduced the RERA Act in 2016, with all the Act's provisions coming into effect from May 2017. Every state is accountable for establishing a Regulatory Authority (RERA), which will administer all the real estate sector's activity and regulate and promote the development of the Real Estate in the country [10].

4.2 Initiatives Under the Housing Sector

The Government of India, along with the governments of the respective states, has taken several initiatives to encourage development in the sector. Housing for all led to the development of several initiatives launched by GoI. A Technology Sub-mission under PMAY (2015) facilitates the adoption of modern, innovative, and green technologies and building materials for better quality and faster construction [9]. In 2017, by the Government of India, for under-construction housing projects and to improvise affordable housing sector, the goods and services tax rates were revised to 5% from the effective rate of 12% and from 8 to 1% [9]. The World Bank creates an ease of doing business index, with higher scores indicating better, typically more straightforward rules for firms and more significant property rights safeguards. India climbed the ranks by making it simpler to do business in four of the report's ten areas of business regulation, including business incorporation, obtaining building permissions, resolving insolvency, and trade. In 2017, the Government gave affordable housing infrastructure status, allowing these projects to benefit from reduced borrowing rates, tax breaks, and larger foreign and private money flows. Later in 2018, the Union cabinet approved the National Urban Housing Fund for Rs. 60,000 crores, situated in Building Materials and Technology Promotion Council (BMTPC), to facilitate raising requisite funds for PMAY. Table 1 showcases initiatives in the housing sector [11].

4.3 Policy Outlook for the Energy Sector

The Energy Conservation Act (E.C. Act) of 2001 was enacted to lower the energy intensity of the Indian economy [12]. The Bureau of Energy Efficiency (B.E.E.), is a statutory entity within the Ministry of Power, oversees driving the economic development of energy efficiency through different regulatory and promotional tools. The Bureau of Energy Efficiency (B.E.E.) was established as a statutory entity at the central level in 2002 to support the implementation of the E.C. Act. The Act establishes regulatory mandates for equipment and appliance standards and labeling, energy conservation construction regulations for commercial buildings, and energy consumption guidelines for energy-intensive businesses [12]. The Government of India created the Energy Conservation Building Code in 2007 to encourage energy efficiency in the building sector. The E.C. Act was revised again in 2010, with the second update of ECBC in 2017 that was limited to the business sector. ECBC (Energy Conservation Building Code), introduced in 2017, applies to significant commercial buildings with connected loads of 100 kW and above or 120 kVA and above. ECBC (Energy Conservation Building Code), introduced in 2017, applies to significant commercial buildings with connected loads of 100 kW and above

Table 1 Initiatives under the housing sector

Initiatives	Year	Information	Remarks
Sub technology mission under PMAY	2015	To encourage the use of contemporary, innovative, and environmentally friendly building materials and technologies to speed up and improve the quality of house construction. It will also make creating and implementing layout ideas and construction plans appropriate for diverse geo-climatic zones easier. It will also help states and cities implement disaster-resistant and environmentally friendly technology	
Ease of doing business	2017	India is now ranked 63rd from 183rd among 190 countries in the ease of doing business index. India ranks 27th in dealing with construction permits, 22nd in getting electricity, and 154th in registering property	
Reduction of G.S.T	2017	To improvise the affordable housing sector, the Government of India cut the goods and services tax rates for under-construction housing projects to 5% from the effective rate of 12% and from 8 to 1% for affordable housing projects	Service Tax exemptions will be continued in G.S.T. as decided by G.S.T. Council Services for works about the Housing for All (Urban) Mission/Pradhan Mantri Awas Yojana (PMAY)
Infrastructure Status to affordable housing	2017	The union budget was announced with Transform, Energies, and Clean India, geared towards infrastructure growth and poverty alleviation. The funding provided affordable housing with infrastructure status. The initiative will enable the affordable housing projects to avail themselves the allied benefits such as lower borrowing rates, tax concessions, and increased foreign and private capital flow	
National Urban Housing Fund	2018	The Union Cabinet approved the creation of NUHF for Rs. 60,000 crores. The fund situated In Building Materials and Technology Promotion Council (BMTPC) will facilitate raising requisite funds until 2022 so that the flow of Central Assistance under different verticals of PMAY-U is maintained	

Source Translated by Author (MoHUA)

or 120 kVA and above [13]. ECBC focuses on the elements like building envelope, mechanical systems, and equipment such as heating, ventilating, air conditioning (HVAC) systems, interior and exterior lighting systems, electrical systems, and renewable energy. The code applies to the five climate zones found in India (Hot Dry, Warm Humid, Temperate, Composite, and Cold). Recent developments in the policies such as revision in National building code (2016), Model building bye-laws (2016), ECBC-R [13], and guidelines by CPWD (2014) are set to increase the overall impact on energy savings potential [13].

National Building Code of India (N.B.C.), is a comprehensive building Code launched in 2005 and revised in 2016, is a national instrument providing guidelines for regulating the building construction activities across the country [14].

The code's provisions are intended to serve as a model for all central, state, city levels and other construction agencies all over the country. In part 11, 'Approach to sustainability' has provided guidelines for making buildings and built environment energy-efficient and environmentally compatible which describes several measures for low energy building design and construction including (1) site, form, and design where the emphasis is on-site design and development; (2) External Development and Landscape, landscape planning and design, rainwater harvesting and irrigation practices; (3) Envelope Optimization focusing on energy-efficient building envelope and its methods, thermal performance, and renewable energy integration; (4) Materials underlining the sustainable alternatives for construction and other efficient building material; (5) Building Services Optimization which discusses about ventilation, passive heating and cooling strategies, HVAC, Lighting: daylighting and artificial lights, renewable energy; (6) Construction Practices; and (7) Commissioning, Operation, Maintenance and Building Performance Tracking [14].

Model Building Bye-Laws are legal guidelines developed by TCPO, which regulate building design and construction characteristics to achieve orderly development of an area and are mandatory [15]. It discusses environmental concerns in Chap. 10, which is incorporated for green structures and sustainability provisions, rainwater harvesting, solar rooftop P.V. norms, and sustainable building materials. It also mentions green building rating systems. Additionally, Chap. 13 includes provision for online building plan approval process and introduction of integrating single-window process. It also discusses the Energy Conservation Building Code requirements prepared by the Bureau of Energy Efficiency, Ministry of Power [15].

The Minister of Power, New and Renewable Energy created and launched the Eco Niwas Samhita, Part–I Building Envelope (Energy Conservation Building Code for Residential Sector) in 2018. It was designed to establish minimum building envelope performance criteria for limiting heat gains (in cooling-dominated climates) and limiting heat loss (in heating-dominated environments), and providing enough natural ventilation and daylighting. The regulation applies to all residential development projects with a plot area of 500 m^2 [13]. The guideline seeks to promote the design and construction of dwellings, including flats and townships, to provide the residents with the benefits of energy efficiency. These have been an integral part of central and state policies and apply to almost all types of buildings. The policies/codes below mentioned highlight the importance of energy efficiency in facilities that are directly/indirectly dealing with energy and their role in respective areas [13].

The governance structure of the state under the energy sector has been illustrated in Fig. 4.

4.4 Initiatives Under the Energy Sector

This chapter draws attention to building rating systems. Green rating methods for buildings assess and evaluate a building's environmental performance. India, presently, has the green grading systems for buildings listed below. The Ministry of

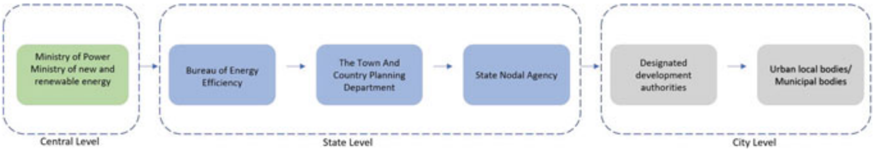

Fig. 4 The governance structure for the energy scenario in India. *Source* Translated by Author (MoP)

New & Renewable Energy (MNRE), the Government of India, and TERI have all recognized the Green Grading for Integrated Habitat Assessment (GRIHA) as India's national rating system for any finished development. It is a tool for measuring and rating the environmental performance of a building. The IGBC Rating System is a program that is entirely voluntary and based on consensus. This grading system would aid in the creation of factories that are energy-efficient, water-efficient, healthier, more productive, and ecologically friendly [16] (Table 2).

4.5 Building Material and Technology

BMTPC has been working since 1990 to implement a comprehensive and integrated approach to promoting cost-effective, environmentally friendly, and energy-efficient innovative building materials and construction technologies for housing in urban and rural areas, including disaster-resistant practices [11]. BMTPC has effectively facilitated the transfer of these technologies from the lab to the field. Upscaling, mechanization, standardization, dissemination, capacity building, and field-level application were all used to support the technologies advocated by BMTPC [11].

BMTPC's activities are focused on providing an enabling environment for affordable housing and sustainable development. The council has been crucial in developing various construction materials and technologies based on agro-industrial wastes during this process. Another area that the commission is pushing is partial prefabrication. Several houses in multiple states have been built for demonstration purposes using pre-fabricated components. The commission has created simple, easy-to-use machines for enhanced production and quality employed in construction with positive results across the nation [11]. The board also aids the Government of India in policy intervention concerns relating to forest conservation, top layer soil conservation, environmental degradation, energy conservation, waste utilization, disaster mitigation, management, etc. The council is conducting performance evaluations of novel and developing materials, technologies, and construction systems for which there are no standards available under the Performance Appraisal Certification Scheme (PACS). So far, 20 P.A.C. (Performance Appraisal Certificates) on various innovative systems and products have been issued as part of the process. Aside from indigenous technologies and materials, the council brings emerging technologies such as Rapid Wall Construction System and Monolithic Construction System. In

Table 2 Initiatives under the energy sector

Industry initiatives	Information	Remarks
IGBC	The Confederation of Indian Industry (CII)'s Green Building Council (IGBC). The council provides a wide range of services, including developing a new green building rating program and certification services	IGBC Green Building Rating Systems include green new/exiting buildings, green residential societies, and homes
GRIHA	GRIHA is a three-tiered green building design evaluation system in which structures are graded. The GRIHA grading system is comprised of 34 criteria divided into four sections: (1) site selection and site design, (2) conservation and efficient resource usage, (3) building operation and maintenance, and (4) innovation	GRIHA for Affordable Housing: All the upcoming projects that have approval/sanction letter issued by government agencies confirming that the project is being developed as per Pradhan Mantri Awas Yojana (PMAY) are eligible for GRIHA AH rating
BEE	BEE created its building grading system based on a 1–5-star scale. The Energy Performance Index was created by B.E.E. (EPI). The unit of Kilo watt hours per square meter per year is used to rate the building, with an emphasis on air-conditioned and non-air-conditioned office buildings	B.E.E. standards and labeling require the display of energy performance labels on high-energy end-use equipment and appliances and the establishment of minimum energy performance criteria
SVAGRIHA	SVAGRIHA was created as an extension of GRIHA and was designed mainly for projects with a built-up area of <2500 m^2. SVAGRIHA may assist in developing and evaluating individual houses, small offices, schools, hotels, and commercial structures, among other things. The rating has only 14 factors, and the U.I. has simplified calculators	

Source BEE, IGBC, GRIHA

this regard, the commission is assessing emerging technologies with the assistance of the Ministry of Housing and Urban Poverty Alleviation's Technology Advisory Group [11] (Fig. 5).

4.6 Introduction to Innovative Technologies

The Pradhan Mantri Awas Yojana-Urban, launched in 2015, will deliver approximately 10 million houses by 2022. To achieve this massive Mission, BMTPC has identified, evaluated, and certified specific systems and technologies. They attempt to bring innovation, speed, safety, and sustainability in the existing construction

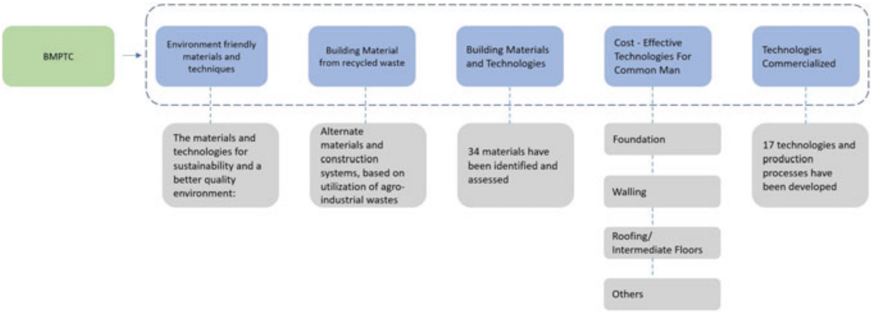

Fig. 5 Building material and construction technologies. *Source* Translated by Author (BTPMC, MoHUA)

methodology without compromising structural and functional performance [9]. To give a further push to these technologies, the Ministry of Housing & Urban Affairs has assertively pursued CPWD, BIS, and state departments to come out with notifications, circulars, S.O.R.s, specifications, etc., authorize state governments to use these new construction technologies in housing projects [9].

CPWD has included New Technology Items in Delhi Schedule of Rates, 2016, Volume-2, and their Analysis of Rates. Further, National Building Code 2016 by BIS, provisions have been updated to ensure utilization of several new/alternative building materials and technologies to provide for innovation in building construction in Part-5 building materials; Part-6 structural design Part-7 construction management, practices, and safety [5]. Also, the third edition of the compendium contains 24 innovative construction systems developed within the country and from aboard. These systems are recommended for use by the public and private agencies based on their technical suitability and certification [5]. Table 3 displays various incentives offered at the state level for green building construction.

The technologies evaluated and suggested will help user agencies choose innovative construction practices, which could be utilized for mass housing schemes. The emerging technologies for mass housing are assessed and certified through the Performance Appraisal Certification Scheme (PACS) of BMTPC [11].

The PACS is a third-party assurance system based on laboratory and field assessments of the requisite performance requirements of any system or construction materials for which no Indian standard exists. The broad characteristics used in the evaluation include, among other things, structural performance against vertical and lateral loads, fire resistance, rain and moisture protection, thermal and acoustic behavior, ease of repairing services, quality assurance, and durability/service life [11].

Table 3 Incentives for green building construction

State	ECBC	IGBC	GRIHA
Punjab	Notified	+5% Floor Area Ratio (FAR) and 100% exemption of building scrutiny fee-free of charge for projects rated Gold or above by IGBC	Additional 5% floor area ratio free of costs shall be permissible to buildings that provide relevant certificates from B.E.E. or GRIHA
Rajasthan	Notified	+5% FAR free of charge for projects which are rated Gold or above by IGBC	Additional 5% free of cost FAR for GRIHA projects in Rajasthan
West Bengal	Notified	+10% FAR for projects which are Pre-certified/ Provisionally Certified as Gold or above by IGBC	10% additional Floor Area Ratio F.A.R. for green building. Building plans for "Green Buildings" will be sanctioned, and additional F.A.R. will be granted, based on pre-certification by the agencies
Uttar Pradesh	Amended	+5% FAR free of charge for projects which are rated as Gold or above by IGBC	Free of cost 5% additional FAR for projects for complying with 4 or 5 Star GRIHA Rating
Maharashtra	Amended	Additional FAR of 3, 5, and 7% for Green Buildings are rated as Silver, Gold, and Platinum respectively by IGBC	The SVA GRIHA linked property tax benefit is in addition to the existing discounts offered by the Municipal Corporation, like the 10% discount to early taxpayers and the 10% discount for females
Jharkhand	Notified	Urban Development and Housing Department, Government of Jharkhand, offers an additional FAR of 3, 5, and 7% for Green Buildings rated by IGBC as Silver, Gold, and Platinum, respectively	FAR of up to 7, 3, 5 & 7% additional FAR shall be awarded to all building uses (except plotted residential) for achieving a 3-star, 4-star, or 5-star GRIHA Rating, respectively
Haryana	Notified	The Government of Haryana (Town & Country Planning Department) offers an additional FAR (Floor Area Ratio) of 9, 12, and 15% for Green Buildings rated as Silver, Gold, and Platinum, respectively IGBC	The Haryana Building Code 2017 incentivizes GRIHA Rated projects by awarding additional FAR of up to 15, 3, 6, 9, 12, or 15% additional FAR shall be awarded to all building uses (except plotted residential) for achieving a 1-star, 2-star, 3-star, 4-star, or 5-star GRIHA Rating respectively

(continued)

Table 3 (continued)

State	ECBC	IGBC	GRIHA
Himachal Pradesh	Amended	+10% FAR for projects for which IGBC grants Gold/Platinum rating	Offers an additional 10% FAR for projects which are given for four and 5-star GRIHA rated building

Source BEE, IGBC, GRIHA

4.7 Incentives for Green Building Construction

Government policies play a very vital role in promoting sustainable development. It is critical to inform national policies to create a much-needed demand for green or sustainable buildings in India. It has also been observed that the Government has a lot of impetus to align the state building codes with the national agenda of promoting sustainability and reducing greenhouse gas emissions (GHG). Furthermore, an ecosystem approach to enhancing the sector has been adopted to ensure the scaling-up and implementation of market-ready solutions [17, 18].

Several incentives have been brought in the market to promote building code and green building rating systems by several state and central government bodies. Following the same, many of the states have been several benefits as listed below.

To increase green construction coverage in the country's residential sector, the CII Indian Green Building Council and the Confederation of Real Estate Developers Associations of India (CREDAI) have signed a memorandum of understanding (MoU) to advance the country's Green building movement [17]. The Confederation of Indian Industrial (CII) aims to develop and preserve a climate favorable to business growth in India, collaborating with industry and Government alike through advising and consultative procedures. CII is a non-government, not-for-profit, industry-led, and industry-managed organization playing a proactive role in India's development process. CREDAI is the nodal body in charge of the most critical infrastructure engine, covering all sorts of works. The collaboration of these two reputable organizations will assure quick progress toward sustainable and green buildings, neighborhoods, cities, and, eventually, a green country [17, 18] (Table 4).

4.8 Schools of Thought

Through vernacular approaches to building design, construction, and operation, the built environment evolves to comply with the modern-day requirements and functions while at the same time integrating the climate-responsive architecture inherent to India. 'Green' building techniques have traditionally been combined with economic, social, and cultural considerations. Thus, vernacular building knowledge has traditionally addressed what we now consider to be 'sustainability'.

Table 4 Industry incentives for green building construction

Initiatives	Information	Remarks
CREDAI	The Confederation of Real Estate Developers' Associations of India (CREDAI) was founded in 1999 with the Mission of advocating for housing and habitat suppliers. Its membership has increased since then, and it now boasts over 20,000 members dispersed throughout 21 states and 220 local chapters	IGBC and CREDAI shall coordinate with the Government-both Central and State-to offer Policy incentives to IGBC rated projects. It will also work for faster environmental clearance for IGBC projects and other Government initiatives
EDGE (Excellence in Design for Greater Efficiencies)	The Confederation of Real Estate Developers' Associations of India (CREDAI) has collaborated with IFC (International Finance Corporation), a member of the World Bank Group, to promote green buildings in India through EDGE certification. EDGE is set to accelerate the mainstreaming of green buildings across the country in a quick, easy, and cost-effective manner	EDGE focuses on building energy and water efficiency. It enables builders and homeowners to select environmentally friendly technological solutions while tracking expenses and expected savings
CII	CII aims to provide world-class advice services in green buildings, energy efficiency, water management, environmental management, renewable energy, green company incubation, and climate change activities	Since 2001, the Indian Green Construction Council (IGBC), a division of CII, has led the country's green building movement with the assistance of stakeholders
Green Co Rating System	GreenCo Rating is a comprehensive framework that evaluates enterprises on the environmental friendliness of their operations using a life cycle approach. It is the "first of its type in the World." GreenCo rating implementation offers organizations leadership and advice on making their goods, services, and processes more environmentally friendly	The Green Company Rating System advocates a performance-based approach. The grading method assesses characteristics against ten criteria Certification is available for both manufacturing and service sector establishments. The rating is applied at the unit or facility level

Source CREDAI, CII, EDGE, GoI

‘Mera Wala’ or ‘my kind of green’ attempts to clarify that ‘green’ is only a direction for achieving greater sustainability and emphasizes that the meanings and understanding of ‘sustainable’ or ‘green’ building are open to individual and contextual interpretation, where what may be required in one case or country may not be relevant for another [12]. The approach emphasizes reducing consumption and pursuing an understanding of sustainability that implies: Use of low technology innovations, materials, and products, which are not ‘brand’ driven; Recognizing’ performance’ and not just’ intent’ of going ‘green’ and; Necessary use of common knowledge [19].

The ‘sustainable communities’ approach has been applied in developing the Manav Sadhana Activity Centre, which is located amidst the largest squatter settlement of Ahmedabad. The campus is built using components prepared through recycling municipal and domestic waste. This process simultaneously addresses environmental concerns, economic issues, and affordable housing [19]. Finally, as the recycled building components are cheaper and of higher quality than the conventional materials, they provide affordable and superior quality building alternatives for the urban poor [19].

Sri Aurobindo Society (S.A.S.) 18 is an international N.G.O. established in 1960, working in multiple fields, including health, education, management, and rural development. ‘Sharanam,’ a purpose-built training center for rural development, has adopted an integrated approach to green building [20] (Table 5).

Table 5 Schools of thought

Initiatives	Place	Information
Mera Wala Green	Ahmedabad	The school attempts to clarify that ‘green’ is only a direction for achieving greater sustainability; the use of identified ‘green’ products or technologies would result in truly ‘green’ or ‘sustainable’ buildings for any context
Sri Aurobindo Society (SAS)	Pondicherry	A purpose-built training center for rural development has adopted an integrated approach to green building
Manav Sadhana Activity Centre	Ahmedabad	The center serves as a training center and activity workshop to manufacture craft-based products using components prepared through recycling municipal and domestic waste. Building products manufactured from municipal and household waste are used in the walls, roofs slabs, doors, and windows. Materials and products were configured to enable construction with simple hand tools

5 Discussion

The belief of a coordinated effort among many players in India's building sector may assist in eliminating the barrier of green building incentives in various ways. The study documented a few collaborations with the help of an extensive literature review. The joint effort might result in creating a minimal set of criteria, which would result in the creation of an easy-to-understand checklist that will aid investors in their decision-making. This list may serve as a helpful starting point for learning the various building rating systems for individuals unfamiliar with green buildings. Of course, stakeholders familiar with the intricacies of these rating systems, such as architects, design consultants, and technology and service providers, may dig further and identify other ways to aid in the growth of the green building market.

Also, when it comes to the residential sector, significantly less data is available on how the green homes are and how they perform when it comes to the consumption of resources like energy and water. Stakeholders can collaborate and come up with solutions that will be beneficial for all. Altogether they can help in generating a more considerable impact in development and creating awareness of green buildings. The future perceptions that can be developed and researched further from this could be the scientific assessment of the sustainability metrics in the industry, standardization and role of standards in sustainable building components, enforcement procedures and legislations to mandate compliance and role of modern technology (Fig. 6).

Fig. 6 Stakeholders in sustainability *Source* Author

6 Conclusion

This study has focused on agendas and policies developed by the government, third-party, and other organizations with a holistic aim towards green building construction and sustainable development. However, there is a need for awareness among stakeholders and occupants for opting toward greener goods. The other possible sectors targeted for sustainable development could be branding and recognition of green products, tractability, and transparency, combined with certifications and developing more initiatives in the domain. More state and city-wise resolutions can be designed to increase the adoption of various codes and policies as they can be customized/adjusted as per the need of the location, and the city-level implementation can have socio-economic benefits. Fulfilling the essential energy demands for future generations and sustainable development can only be achieved through minor, diversified energy-efficiency initiatives and process transformation in all end-uses and applications in all sectors.

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Entrepreneurship for Differently-Abled People: Getting Ahead with the Help of Assistive Technology and Policy Support

Simran Sodhi and Amit Kumar Dwivedi

1 Background

Whenever we hear the term “disabled”, our mind always functions toward the difficulties that differently-abled people face every day. These differently-abled people need empathy and emotional support to live respectable life. Further, we may think of the changing scenario in the lives of the differently-abled population. But the change has a history with years of struggle and contributions of some renowned social activists and personalities. Literature takes us to the time when the differently-abled were the subject of superstition, persecution, rejection and even stated to be the devil’s substitutes. Later, the differently-abled people (termed as ‘disabled people’ or ‘people with disabilities’ before 1980s) struggled to save their lives but could not contend when people considered them as the primary target for amusement and ridicule. Gradually, some communities came forward and acknowledged their responsibilities towards differently-abled people. Slowly, efforts were made that helped differently-abled people be a part of the local environment. Barnes [1] eighteenth century, which is remarkably evoked by the industrial revolution, brought a significant change in our society. This transformation has affected all segments of society. Even the differently-abled population could not leave unaffected due to this dissemination. These speedy factories with enforced discipline, timekeeping and production norms were unfavourable for slower and flexible methods of work into which many differently-abled people were unified [1]. By the mid-90 s, we can observe the society’s softening of behaviour towards the disabled and an attempt to integrate them into the community.

For a considerable time in history, differently-abled people were confined only to the home. In 1970s, the “Independent Living Movement” attracted attention in the USA. Some differently-abled activists put much effort into this movement, resulting

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in a policy shift in a new direction. After this, the American Universities introduced self-help programmes that helped differently-abled people enrol in the mainstream programme [2]. At the same time, the UK witnessed the activism of differently-abled people for their inclusion in paid work [3]. Countries like the United States, UK, Europe, South Korea, and Australia took significant steps to include differently-abled people in society, educational programmes, and paid work. Still, all these efforts could not lead to the desired results due to some or other reasons. More than 60% of differently-abled people of working age are unemployed [2]. Further, many academicians and scholars came up with a solution for the inclusion of differently-abled people. Today, the locus is shifted from paid work to entrepreneurship. It is believed that the best option for the differently-abled population is to engage in entrepreneurial activities. Many nations across the globe have realized the opportunities for differently-abled people in entrepreneurship and come up with various support that can help these people start their enterprises [4].

Research Objectives

- This paper aims to understand how entrepreneurship should be used to empower differently-abled people to make an inclusive and sustainable economy.
- The paper majorly studies the role of assistive technology that would help differently-abled people work more independently. It further brings to view the role of government policies and initiatives in availing these technologies to the needful.
- There is not much literature on differently-abled entrepreneurship and how assistive technology can be a game-changer for such entrepreneurs. Authors have identified the works published and easily available at the open platform for the reader. This research is a precursor to a systematic literature review which will be performed based on the feedback that authors would receive.

2 Methodology

A literature review of existing literature is performed to analyze various researched themes under "differently-abled people", "entrepreneurship", "assistive technology", "government policies". Therefore, the current review paper discusses entrepreneurship opportunities for differently-abled people and how assistive technology could be the major support for them. The papers were extracted from the Google platform. Considering the broader scope of literature, no specific database or journal was contemplated. This helped in relevant data collection from various databases to substantiate this study. Some book chapters and conference paper were also included as they were relevant to the context. It is essential to highlight that papers authored other than the English language were excluded from this study.

In the search strategy, the data was retrieved through keywords, which are; "differently-abled people" or "disabled people" or "people with disability" and "entrepreneurship" and "assistive technology" and "policies for differently-abled people" or "policies for disabled people" or "policies for disabled entrepreneurs" "policies for differently-abled entrepreneurs". This search provided us a database of 35 papers. After a thorough assessment, 23 papers were included for this research. The search includes paper published up to 12th March 2021. All the abstracts of accumulated papers were read and few papers were excluded as per the generating theme. Although after abstraction reading some relevant papers and reports were further added to the data collected. Mainly, the literature on policy work and current action plans for differently-abled people and entrepreneurship among different countries was added further.

3 From Possibility to Practice

Most differently-abled people have faced many issues while searching for some traditional jobs for themselves. Some of these people can find a job, but they cannot handle the discrimination they had to face at their workplace due to their disabilities [5]. Therefore, it is being observed as a global phenomenon that differently-abled people are vastly underrepresented in the workforce. Across nations, the government has turned up various employment schemes for differently-abled people. Still, these people have been at maximum risk in context to economic inequality. Even at the time of economic rebound, workers with disabilities have seen extremely slow improvement as there was a gradual increase in the workers without disability but a drastic decrease in the workers with disability [6]. With time, many differently-abled people thought of starting their enterprise. Many academicians and scholars also came up with entrepreneurship as a suitable choice for differently-abled people. These days many differently-abled people have already started their businesses. Instead, some nations have recorded a higher rate of enterprises by differently-abled people (12.2%) than people without disability (7.8%) [5].

4 Not a Forced Choice

Some may think that the proposal regarding entrepreneurship among the differently-abled cropped up because of their difficulties in paid jobs. This can be one reason but not the major one. Lately, academicians and scholars have studied the characteristics and competencies of disabled people. The literature from various studies, majorly psychology and sociology, has done much work on understanding the surroundings, characteristics, competencies, and behavior of differently-abled people. Considering such studies, this paper tries to draw attention to the fact that differently-abled people have all primary competencies that are evident in a successful entrepreneur. Further, these facts justify that entrepreneurship is not a forced choice for differently-abled people to be economically abled and economically inclusive. Till now, no study has focused on entrepreneurial competencies among differently-abled people. Few studies have given entrepreneurship an option as differently-abled people face a lot of resistance and difficulties in paid jobs.

A study on abled and disabled athletes tries to understand the motivation level among both groups. And according to that study, there is no difference in the motivation level of abled and disabled people [7]. Instead, it shows that disabled athletes have a high level of motivation. According to various socio-cultural theories, the motivation within an individual is the outcome of his actions and activities. Further, motivation directly impacts an individual performance as well as the level of success. A motivated person would possess a need for achievement. In differently-abled people, we can observe a high level of motivation, which influences their performance and level of success, leading to a desire for further accomplishment. Thus, a cycle of performance, success, and accomplishment increases the need for achievement in an individual. As mentioned earlier, motivation is the outcome of actions and activities. This is how a differently-abled person is when involved in entrepreneurial activity; a small accomplishment gives him immense motivation, further pushing his need for achievement. This provides us with a picture of a successful entrepreneur. Studies have proven that there is no significant difference in the Intelligence quotient of abled and differently-abled people. Gradually, scholars tried to find out the difference in emotional intelligence (EI) among abled and differently-abled people. As per the results, differently-abled people show a higher level of emotional intelligence than abled people [8]. Considering the role of emotional intelligence in the success of an enterprise, we can say that differently-abled people are very suitable as an entrepreneur. We have many examples where entrepreneurs have failed only because of a low level of emotional intelligence. And the current studies have proven the significance of EI for the stability, growth, and success of an enterprise. The American Psychological Association (2014) defines resilience as "the process of adapting well in the face of adversity, trauma, tragedy, threats or even significant sources of stress" [9]. This examines how an individual responds to stressful experiences. A person with high resilience generates behavior that helps in a positive attitude towards stressful situations. Resilience and Emotional Intelligence are directly connected. It is believed that the resilience of a person is dependent on EI. If a person has a high level of emotional intelligence, it will lead to high resilience in that individual. A differently-abled person has a high level of EI compared to an abled person, which directly indicates that a differently-abled person also possesses a high level of resilience compared to abled people [10].

According to research, the self-esteem of differently-abled people is low as compared to abled people. But, this is one factor that can be improved within any individual. It is believed that through some contributions, differently-abled people could be helped in increasing their self-esteem. Many countries have focused on the development of assistive technology for differently-abled people. Along with development, these countries are also providing training to differently-abled people to use such technologies. As a result, they can perform many activities themselves, which was earlier not possible for them. Assistive technology also helps them in making them socially inclusive. The overall outcome of these initiatives is an increase in self-esteem in differently-abled people.

5 Assistive Technology Up-Gradation and Government Intervention Through Policy Support

Assistive technology is any equipment, item, or product that helps increase, maintain, or improve the functional capabilities of differently-abled people. Such technologies include hearing aids, low vision devices, augmentative and alternative communication systems, walking frames, artificial legs, and wheelchairs [11]. Generally, assistive technology is categorized into three broad types: sensorial aid systems, physical aid systems, and cognitive aid systems [12]. The differently-abled people inceasingly use robotic assistive devices. These devices help them in much independent life with more functionality in physical tasks [13]. Majorly, assistive technology affects the motivation and esteem of differently-abled people. Through technological assistance, differently-abled people feel more abled in performing tasks and participating in the social environment, which increases their self-motivation and self-esteem [14]. As mentioned earlier in the paper, differently-abled people lack self-esteem. Assistive technology plays a significant role in improving their self-esteem. Countries like Malaysia are focused on providing training to differently-abled people from the very initial stage. They equip them with suitable assistive technology as well as provide primary education and skills training for entrepreneurship [14, 15].

Assistive technology plays a significant role in the lives of differently-abled people. And understanding this factor, scientists have come up with advanced technologies over the years. Gradually, we can observe much improvement in assistive technologies. Researchers found that steering conventional wheelchairs was a challenge for differently-abled people. After that, technology came up with an up-gradation such as a joystick mechanism in a wheelchair. Likewise, many inventions helped people suffering from Parkinson's disease [13]. Today, we are at the stage where we have technologies like chin and head-based controls, robotic wheelchair arms, augmented reality, and exoskeletons. Industry 4.0 has contributed significantly to the development of assistive technology. Voice control assistive technology is one of these developments. Internet of things (IoT) made it possible for differently-abled to command the technology just by thinking. Technology is connected to the neurological part of humans. Devices are being developed through which blind people are able to see. Just a chip inserted in the brain can do wonders and make a person abled to perform any task without hassle. The fourth industrial revolution indicates the increasing quality of industrial production by integrating machines and people. It is moving towards a future in which collaboration of robots and people takes place with the support of intelligent assistive systems and web technology. This technological up-gradation has made differently-abled people more confident [12].

Many countries have taken the initiative towards focused policies for differently-abled people. But the current buzz is about the concentrated policies on entrepreneurship among differently-abled people. At first, countries turned up with policies that helped the differently-abled attain proper education; later, countries came up with policies supporting differently-abled people in getting paid work. But slowly, with the current situation, the trend is towards concentrated policies for entrepreneurship among differently-abled people. US Department of Labor has the Office of Disability Employment Policy (ODEP) has introduced a policy that concentrates on self-employment and entrepreneurship. Under this policy, the government fosters partnership among federal, state, and local levels to support individuals with a disability with the help of financial support and accessibility of resources [16]. European Union has worked on various strategies at different platforms to encourage entrepreneurship among differently-abled people in Europe. A project called 'European Research Agendas for Disability Equality' was started that engaged civil society organizations as agents of change that would influence the future priorities for European disability research [17]. In Europe, some countries have witnessed higher self-employment among differently-abled people than people without any disability. In this regard, a significant gap is seen in countries like Greece, followed by Romania, Portugal, Cyprus and Poland [18]. The government of Europe is very focused on factors like: increasing awareness about the feasibility of entrepreneurship, developing entrepreneurship skills, ensure access to appropriate financial support, improving internet and IT accessibility for differently-abled people, and development, acquisition and use of assistive technology. European countries are some of the very few countries rigorously working on assistive technology development for differently-abled people. World Health Organisation has established a Global Cooperation on Assistive Technology (GATE). This initiative is partnered with international organizations, donor agencies, professional organizations, academia, and user groups, to improve access to high-quality affordability assistive worldwide. Assistive technology for the betterment of differently-abled people is a global dynamism today.

6 The Indian Scenario

India is home to 138 crore people [19], out of which 2.68 crore people are differently-abled, which accounts for 2.21% [20] of the overall population in the country. Being a developing country, India is very focused on the overall growth of every segment of the country. India has implemented social inclusion strategy, where every section of the country would be uplifted. For this, the Government of India has turned up with various schemes and projects at different points in time. Considering inclusion as a factor, the government has schemes for some focused groups like schemes for women, schemes for the rural population and many more. Likewise, one focused group called the "disadvantaged sector" consists of minorities, women, SC, ST, differently-abled people, etc. Therefore, the government offers concentrated schemes for women, minority, SC, ST, and other backward classes within disadvantaged societies. With such schemes, the government is making them economically inclusive. Still, one segment in the disadvantaged group remains in the dark—"differently-abled people". The government has schemes for differently-abled people, but they help make them socially inclusive but not economically inclusive. As India is moving towards an entrepreneurial ecosystem, we can witness several projects and schemes to encourage entrepreneurship and startups in India in the last few years. Again, there are no such initiatives for differently-abled people in India. As discussed earlier, rather than employment, differently-abled people are moving towards entrepreneurship. And this is not only because of the challenges they face in labor and paid jobs but also because of their entrepreneurial competencies. This phenomenon has been witnessed globally. Countries like United States, United Kingdom, and Greece are tremendously working towards entrepreneurship among differently-abled people [4]. However, this goal cannot be achieved without the intervention of governments. Government intervention for entrepreneurship for differently-abled people is crucial. However, this alone will not create a success story. An equal contribution is required in the development of assistive technology.

7 Discussion

As the focus is shifting towards social inclusion to economic inclusion among disabled people, the government came up with policies that would increase the employability of differently-abled people. But eventually, it was observed that differently-abled people are not able to find suitable jobs in the market. After various schemes and policies, the employment rate among the differently-abled has declined over the years. Slowly, in places like the United States and Europe, the government shifted its focus from employability towards entrepreneurship among differently-abled people. On the other hand, we can observe the development of assistive technology for differently-abled people. These assistive technologies help in increasing, maintaining, and improving the functional capabilities of differently-abled people [23]. The technology is designed in a way that could make these people more abled in performing tasks independently. Whether social inclusion or economic inclusion, entrepreneurship among differently-abled people and equipped them with suitable technology goes hand in hand. Countries that are proposing entrepreneurship as an option are highly focused on the up-gradation of assistive technology for differently-abled people. Even to perform entrepreneurial activities smoothly, differently-abled people need suitable technology. Otherwise, there is a higher probability that the entrepreneurial schemes will end up in the same manner as employability schemes for differently-abled.

From the above facts, it is prominent that assistive technology plays the most crucial role for differently-abled people, be it social inclusion or economic inclusion. And the entrepreneurial aspect among differently-abled is highly proportionate with suitable assistive technology.

According to research, seventy per cent of differently-abled people face major economic issue [21], and only ten per cent of potential beneficiaries get access to assistive equipments [11]. The situation is alarming when it comes to low and middle-income countries. These assistive technologies require high investments, which make it difficult for low and middle-income countries. Financial constraints, scarcity of trained personnel, and low resources restrict assistive technology development [11, 12]. This could be a possible reason we see a lot of assistive technological development in countries like the US and Europe and comparatively lower in countries like India. Even if the technology is made available, because of economic constraints, differently-abled people cannot get access to suitable technology. The availability of low-cost technology will make it feasible for the larger population of differently-abled to use technology in daily living [13]. Researchers also suggest that these technological developments should be done considering the true environmental, social, and resource factors that could impede technology adoption in low-resource settings [11]. Because of the above-mentioned facts, national policy framework for assistive technology is highly required [22]. According to World Report on Disability (2011), inadequate policies are key challenges in low and middle economies that challenge the accessibility of technology among differently-abled. Researchers also believe that lack of understanding and information among policymakers also leads to such challenges. So, policymakers must pay focused attention to the development and accessibility of assistive technology for inclusion of differently-abled people. Lack of research in is another factor that hinders the development of technology and ignorance among policy makers [21]. OECD reports also focus on the fundings for the development of assistive technology and how this would be helpful for differently-abled entrepreneurs [14]. GATE Workplan also discusses the requirement of the national policy framework for assistive technology [11].

8 Conclusion

Differently-abled people have come a long way from social exclusion to economic inclusion. Earlier, differently-abled people were not considered to be part of society. Gradually, with the help of some social groups, differently-abled people got inclusion in the community. It took them considerable time to be a part of paid job groups. But, with time, the employability rate among differently-abled people had declined even when employability in the market was increasing. Slowly, differently-abled people found a suitable option for them – Entrepreneurship. With this shifting trend, there is a buzz about entrepreneurship as a livelihood option for differently-abled people. Parallelly, with the help of shift in the industry as Industry 4.0, we observe development in assistive technology. Earlier, there were technologies for differently-abled people; however, with the up-gradation through Industry 4.0, technology got more sophisticated. This developed technology helped differently-abled people by making them more abled in performing the tasks independently and more efficiently. This development made them more inclusive socially as well as economically. It was gradually realized that if supported with appropriate assistive technology, entrepreneurial development would help the differently-abled become more inclusive.

We could observe the initiation of policy support in some countries for the entrepreneurial aspects for differently-abled, but there is little policy support by the government regarding assistive technology. Ignorance of policymakers for assistive technology affects the availability of existing technology among differently-abled. It is imperative to understand that entrepreneurial development also needs the support of assistive technology if we want to include differently-abled people socially and economically.

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Does University Entrepreneurial Ecosystem and Entrepreneurship Education Affect the Students' Entrepreneurial Intention/Startup Intention?

Raj Karan Gupta

1 Introduction

Today, the growing unemployment has become a serious concern particularly for developing countries like India. Further, the Covid-19 pandemic has badly affected the entire economy of the nation and unemployment has increased because of this pandemic effect. In this kind of crisis, it has become relevant not only to strengthen the exiting startups/enterprises but also to devise some mechanism/policy framework to encourage individuals to become entrepreneur and create new startups. This will also be helpful to address the unemployment problem of the nation along-with ensuring a rapid economic growth and development. As we know that the major portion of the job seeking force comes from the universities and other higher education institutions after completing their courses which further requires more jobs. Universities and higher education institutions can play an important role in motivating and encouraging their young students towards their entrepreneurial career/startup as a choice of their career option. But to do so, one needs to understand the students' entrepreneurial intention as it is a widely accepted fact that intention is the best predictor of the individual's behavior. Universities play an important role in shaping entrepreneurial intention/startup intention of their young students by not only providing entrepreneurial education in their curriculum but also helping them by creating an appropriate entrepreneurial ecosystem.

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2 Need and Importance of This Study

As we all know that today unemployment is growing at a very fast rate and the entire world is concerned about this. The problem of unemployment is more serious in developing and under developed countries. In India where about 65% population is below the age of 35 years creates a challenge of providing jobs to its large job seeking force. Further, if the nation is not able to provide job opportunities to its youths/job seekers, that may further create issues like social unrest, inequality of wealth, and poverty as well. However, it is very difficult for a nation to provide jobs to all its job seekers and hence the solution lies in creating a pool of job creators/entrepreneurs. But to create more entrepreneurs, there is a need to develop entrepreneurial intention among the students as they can be transformed as a good job creators through motivation, entrepreneurial education and also by providing a good university entrepreneurial ecosystem. There are several studies which have established relation between entrepreneurship education and entrepreneurial intention, but at the same time it is very hard to find good studies specially in Indian context which are in the area of establishing a connection between university entrepreneurial ecosystem and students' entrepreneurial intention. By realizing this need, this study is formulated which tries to understand and explore the impact of university entrepreneurial ecosystem and entrepreneurship education on students' entrepreneurial intention. The findings of this study will be helpful in developing a startup policy specially a policy for developing a good entrepreneurial ecosystem in the institutions of higher education.

3 Literature Review and Hypotheses Development

3.1 Entrepreneurial Intention and Entrepreneurial Ecosystem

There are several studies which have tried to define entrepreneurial intention. According to Isiwu and Onwuka [1], "entrepreneurial intention can be defined as one's desire, wish and hope of becoming an entrepreneur". In another study [2], entrepreneurial intention is defined as a state of mind of an individual which directs their behaviour towards development and implementation of new business concepts and ideas. Hence, the entrepreneurial intention can be well understood as a conscious state of mind that precedes actions and also directs an individual's behaviour towards setting up a new venture. Regarding entrepreneurial ecosystem, there is no single definition of entrepreneurial ecosystem and different authors have defined in their own way. According to Isemberg [3], the entrepreneurial ecosystem is a set of individual elements which are combined in a complex manner. Further, ecosystem may vary as per the available technology, network intensity and also by the organizational variety [4]. Phan et al. [5], Kingma [6], Rice [7], Auerswald [8], Bell-Masterson and

Stangler [9], Guerrero [10], Miller and Acs [11], Breznitz and Zhang [12] described 'entrepreneurial ecosystem' as a mechanism which includes various elements/actors like incubators, science parks, government, accelerators and also the universities as well. Further, there may be differences in various universities for providing their services to their regions [13]. Entrepreneurial ecosystem can be described as a guide which provides a framework for the policy makers for developing effective entrepreneurial policies [14].

3.2 University Entrepreneurial Ecosystem and Entrepreneurial Intention

There are several studies which have established the role of university entrepreneurial ecosystem in developing entrepreneurial intention. University entrepreneurial ecosystems can be seen as an important facilitator towards developing entrepreneurial capabilities and competencies to develop the entrepreneurial spirit among students. According to Stam [15], university entrepreneurial ecosystem can be considered as interdependent set of various actors which are governed and controlled in a manner that it can facilitate the entrepreneurial actions. Few studies says that universities are the fundamental agents for the entrepreneurship development [16–18]. To be successful in business, the business organizations not only required a good strategy and related capabilities but also resources, networks, and government support [19]. Few other studies [17, 20] also found a close relationship between the university context and students' entrepreneurial intention. In a study [21] the authors examined the direct relationship between university environment and students' entrepreneurial intention and found university environment as more influencing factor as compared to personality trains or other socio-economic factors in shaping entrepreneurial intention. One more study [18] examined the relationship between supportive university environment and entrepreneurial intention among the university students of Turkey. Another study in this area [22] investigated and examined the effect of university department characteristics on entrepreneurial intention and revealed that entrepreneurial education along-with industry ties affect the entrepreneurial intention. Few other studies [23–25] established a relation between university entrepreneurial support programmes and entrepreneurial intention. These studies found that there is a positive relationship between university entrepreneurial support programmes and the students' entrepreneurial intention. Studies like [17, 20, 25] concluded that entrepreneurial support in a university context increases the intention of students towards creating a new venture. Thus, after going through the available literature the following hypothesis was formulated:

H1: University entrepreneurial ecosystem positively affects the entrepreneurial intention of their students.

3.3 *Entrepreneurship Education and Entrepreneurial Intention*

Several studies have made their contribution towards understanding the role of entrepreneurship education in developing entrepreneurial intention. Entrepreneurship education can be considered in terms of all kind of educational activities with a purpose to develop entrepreneurial intention among students [26]. In a study [27] entrepreneurship education was described in the form of teaching & learning activities that is helpful in determining and developing entrepreneurial attitude. In another study [28] it was found that entrepreneurship education develops entrepreneurial awareness and skills among students and also helps them towards their entrepreneurial career. In studies [29, 30], it was concluded that a robust correlation exists between entrepreneurship education and entrepreneurial intention. They found that entrepreneurship education offered at university equips students with the necessary knowledge and skills required to pursue their entrepreneurial career. Besides, few more studies [31–33] also believe that entrepreneurship education can be used to stimulate an entrepreneurial mindset among students. In another study [34] it was found that entrepreneurship education plays an important role in the development of entrepreneurial intention among the students. Hence, after studying the mentioned literature available in this area it is assumed that entrepreneurship education has an effect on entrepreneurial intention and the following hypothesis was formulated in this regard:

H2: Entrepreneurship education positively and significantly affects students' entrepreneurial intention.

4 Objectives

The objectives of this study are to:

1. Investigate the impact of university entrepreneurial ecosystem and entrepreneurship education on the students' entrepreneurial intention/startup intention.
2. To explore the causal relationship among the independent and dependent variables.
3. To provide some valuable measures for the purpose of developing university entrepreneurial ecosystem aiming to enhance students' entrepreneurial intention/startup intention.

5 Research Questions

This study addresses the following research questions:

1. To what extent the university entrepreneurial ecosystem affects the entrepreneurial intention/startup intention of the students?
2. What role the entrepreneurship education plays in shaping the entrepreneurial intention/startup intention of students?

6 Methodology

6.1 Data Collection

Data have been collected by using a structured questionnaire. The questionnaire contained two sections. Section-I contained the questions relating to the demographic information of the respondents while section-II of the questionnaire contained the items asking data on the various variables used in this study. A total of sixteen items were used (six items to measure entrepreneurial ecosystem; five items for entrepreneurship education and five items to measure the entrepreneurial intention). The items of the questionnaire are provided in Appendix-1 at the end of this study. The data were collected from the undergraduate students from business and management discipline in the age group of 17–26 years. The sample was taken from a private university located in Greater Noida, Gautambuddh Nagar, U.P., India. The data were collected through online and offline mode. A total of 186 responses were found usable and were considered for further analysis. Out of 186, 112 responses were received from male respondents and 74 responses were from female respondents. The items were designed to be rated on a five-point Likert scale (1 for Strongly disagree to 5 for strongly agree). The reliability of the instrument was also conducted and Table 1 contains the details of the reliability test of the instrument.

Table 1 presents the reliability Statistics details. The Cronbach's Alpha value was found 0.895 for all the 16 items used in this study and the said Cronbach's Alpha (0.895) indicates that used instrument for this study is a reliable instrument.

Table 2 presents the details of the item total statistics. No item has been deleted from the used 16 items as the overall Cronbach's Alpha (0.895) is already good and because no significant increase in the overall value of Cronbach's Alpha was found in case of if any item deleted and hence it was decided to retain all 16 items of the questionnaire.

Table 1 Reliability statistics

Cronbach's Alpha	N of Items
0.895	16

Table 2 Item-total statistics

	Scale mean if item deleted	Scale variance if item deleted	Corrected item-total correlation	Cronbach's alpha if item deleted
E_E1	59.4247312	54.483	0.628	0.886
E_E2	59.4139785	55.757	0.567	0.888
E_E3	59.3709677	56.181	0.575	0.888
E_E4	59.3225806	56.295	0.539	0.889
E_E5	59.4408602	55.426	0.582	0.888
UEE1	59.4462366	55.405	0.506	0.891
UEE2	59.5107527	53.549	0.695	0.883
UEE3	59.4623656	56.499	0.545	0.889
UEE4	59.6075269	54.283	0.651	0.885
UEE5	59.7795699	55.902	0.449	0.893
UEE6	59.7795699	56.432	0.467	0.892
EI1	59.4086022	55.000	0.570	0.888
EI2	59.5376344	54.942	0.591	0.887
EI3	59.2365591	56.528	0.526	0.890
EI4	59.2795699	56.202	0.574	0.888
EI5	59.4301075	58.084	0.460	0.892

6.2 Data Analysis

Data have been analyzed with the help of SPSS version 21 software. To explore the relationship among independent and dependent variables, correlation and regression analysis were performed.

7 Findings and Discussions

Table 3 presents the details of the correlation statistics. A positive and moderate correlation has been found among both the independent variables (University Entrepreneurial Ecosystem + 0.578 and Entrepreneurship education + 0.590) consecutively with the dependent variable Entrepreneurial Intention.

Model summary is presented in Table 4. The R square value has been found (0.450) which means that the independent variables (University entrepreneurial ecosystem and Entrepreneurship education) are explaining 45% variation in the dependent variable (Entrepreneurial intention) of this study.

Table 5 presents the details relating to the coefficients. It has been found that university entrepreneurial ecosystem (0.367) with the p-value < 0.05 supports H1 hypothesis and the coefficient value for entrepreneurship education (0.411) with a

Table 3 Correlations

		E_Intention	E_E	UEE
E_Intention	Pearson Correlation	1	0.590[a]	0.578[a]
	Sig. (2-tailed)		0.000	0.000
	N	186	186	186
E_E	Pearson Correlation	0.590[a]	1	0.517[a]
	Sig. (2-tailed)	0.000		0.000
	N	186	186	186
UEE	Pearson Correlation	0.578[a]	0.517[a]	1
	Sig. (2-tailed)	0.000	0.000	
	N	186	186	186

[a] Correlation is significant at the 0.01 level (2-tailed)

Table 4 Model summary

Model	R	R square	Adjusted R square	Std. Error of the estimate
1	0.671[a]	0.450	0.444	0.45830

[a]Predictors: (Constant), UEE, E_E

Table 5 Coefficient table coefficients[a]

Model		Unstandardized coefficients		Standardized coefficients	t	Sig
		B	Std. Error	Beta		
1	(Constant)	0.988	0.257		3.839	0.000
	E_E	0.411	0.066	0.398	6.215	0.000
	UEE	0.367	0.063	0.372	5.799	0.000

[a]Dependent Variable: E_Intention

p-value < 0.05 also supports H2 hypothesis of this study. Hence, it can be said that both university entrepreneurial ecosystem and entrepreneurship education offered by the university are positively affecting the students' entrepreneurial intention. In addition to that the Beta value of Entrepreneurship education has been found (0.398) which means that entrepreneurship education is more influencing factor in shaping entrepreneurial intention as compared to entrepreneurial university ecosystem.

8 Conclusion, Suggestions. Limitations and Future Direction of Work

The main conclusion of this study is that both university entrepreneurial ecosystem and entrepreneurship education have a positive impact on shaping the entrepreneurial intention of the students and hence requires to be strengthen. As entrepreneurship education has been observed more influencing factor, more emphasis should be towards providing a good entrepreneurial education specially selection of appropriate pedagogy like "learning by doing" and/or 'action learning' or 'project-based learning' to offer more opportunities to the students to explore more on their practice-oriented learning. The focus should also be on 'Teaching for entrepreneurship' to prepare students for their entrepreneurial career.

This study has also its own limitations. One of the limitation of this study is that it does not use a very large sample size as the sample size of this study was 186 respondents and the sample was taken from the students of one private university. And hence, the findings of this study cannot be generalized at large. However, still this study gives a basis and direction for conducting some more work by incorporating more respondents with a larger sample size and including more institutions as well. The findings of this study also raise few questions like why university entrepreneurial ecosystem is less affecting the entrepreneurial intention. And hence this study gives an opportunity to further investigate and provide answers to such questions. Though clear answer to such questions can only be given when someone investigates this through other studies, however, one of the possible reason behind such findings might be that entrepreneurial education is more important for Indian students as entrepreneurial ecosystem. Because with the entrepreneurship education, students might feel more confident towards their entrepreneurial career and a student with great confidence & efficacy can struggle and find solutions to its business problems. In addition to that it also gives a direction to entrepreneurial policy makers towards formulating good entrepreneurial policies for higher education institutions (HEIs) as students are the major source of new entrepreneurial ventures/startups.

Appendix 1: Items used in the Questionnaire

University Entrepreneurial Ecosystem

UEE1: In my opinion, the university ecosystem is helpful in providing services in identifying and exploiting good business opportunities.

UEE2: I perceive university entrepreneurial ecosystem helpful in developing innovative ideas.

UEE3: The university ecosystem has motivated me towards my entrepreneurial intention.

UEE4: My university has a policy to provide financial support to its students for starting a new venture.

UEE5: My university ecosystem is helpful in developing good professional contacts required for setting up a new enterprise.

UEE6: My university do enough to create an awareness of entrepreneurship as a good career choice.

Entrepreneurship Education

EE1: In my opinion, Entrepreneurial learning is helpful in developing entrepreneurial knowledge & shaping entrepreneurial intention.

EE2: By teaching entrepreneurship, one can stimulate entrepreneurial spirit among the students.

EE3: Entrepreneurial and business educational programmes on campus helps students in their decision to become entrepreneur.

EE4: My entrepreneurial education has equipped me with the necessary knowledge and skills required to become entrepreneur.

EE5: I also agree that entrepreneurial education offers adequate support to practice the entrepreneurial knowledge through entrepreneurial exercises.

Entrepreneurial Intention

EI1: I will prefer to start my own venture/business rather looking for a job.

EI2: I am ready to do anything that needs to be done to become an entrepreneur.

EI3: I am very much willing to create and develop a new venture in near future.

EI4: I would strongly prefer to go for an entrepreneurial career rather than to become an employee.

EI5: To become an entrepreneur is one of the important goals that I would like to achieve.

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Types of Designers and How to Develop Them

Amaresh Chakrabarti

1 What Design is and What that Implies

As described by Cross [1], design is an "interdisciplinary discipline". As discussed in [2], design has a variety of definitions, largely of two kinds: as a process or activity—the act of designing, or as an outcome—the designs developed from the process or activity. Discussion on types of designing and designers need a definition of design that is generic enough to include the various forms that a designer takes, as needed by the various forms of designs and designing, and all associated phenomena, carried out by designers. According to Simon [3] design is "a purposeful activity aimed at changing existing situations into preferred ones." Adapting this, we take *a design as a plan for intervention* which, when implemented, is intended to change an undesirable situation into a (less un-) desirable one. *Designing is the process of identifying these situations as well as developing designs* to support the transition. As discussed in [2, 4–6], this implies several generic features of design:

- Designs are plans for intervention that may (not) include physical artefacts; hence the need for designers to have a *generic view of designs.*
- Undesirable and desirable situations are essential for designing; without the undesirable, designing is meaningless; hence the centrality of understanding the *lifecycle of the system to be improved, with its stakeholders, their needs and aspirations arising in any part of the lifecycle.*
- Designing involves identifying these situations as well as developing the plan with which to change the less into more desirable; hence the need for *designing both problems and solutions.*

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- It is the implementation of the design that actualizes change: *designing and implementing (realisation, services and business) are both crucial* in bringing about the change. A designer should therefore be trained in this whole process of innovation.
- A design is implemented aiming to effect the desired change, which may not happen; hence the *need for design science* to inform and support the practice of design and its education.

2 Innovation and Design

Overall, the innovation process, whereby a system is designed and brought to the society, involves design of products, their processes of realisation (e.g. production), the service systems and supply chains, and the business systems that can bring these to the society. Innovation can therefore happen in any of these four elements, which, therefore, have to be designed. *Innovation is transactional between society, that demands value, and the business that offers a system as a value proposition to the society.* This exchange is sustainable only when it is win–win for both business and society, where society receives its value and business receives its profit in return. *Business develops these systems by supplying, integrating or inventing technology, while operating within the constraints of the fragile ecology of the Earth*, so as to offer value for the society; innovation is the process through which this value is created and enabled; design is the engine of innovation.

The types of knowledge needed for designing are proposed by various researchers. For instance, Cross [1] identifies three major areas from which design knowledge is drawn: people, process and the artefact being designed. Blessing et al. [7] propose six 'facets' (i.e. areas of influence): people, process, artefact, organisation, knowledge/method/tools, and economy; later [6] 'ecology' has been added to this list.

In order to investigate the specifics of design knowledge, Kota and Chakrabarti [8] carried out a comprehensive analysis of design models from literature, and identified six dimensions that together form the state-space in designing: *Activities* of designing (generate, evaluate, select, etc.); *Criteria* for designing (performance, cost, safety, look, quality, manufacturability, social aspects, price, etc.); *Lifecycle Phases* (material, production, usage and after-usage, etc.); *Outcomes* of designing (requirements and solutions); *Design Stages* (task clarification, conceptual design, embodiment design and detail design, etc.); and the *System* being designed (assembly, relationship, part, feature, etc.); the existence of these dimensions have been verified using empirical studies of designing. Further, various authors e.g. [9, 10] have verified the existence of both *synthesis* (the divergent process of generating new constructions during designing, expanding the number of alternative options) and *analysis* (the convergent process of assessing the worth of these constructions, narrowing down the number of options). Further, literature has identified both *problem finding* and *problem solving* as essential parts of designing e.g. in [10].

3 Variants of Designing

The knowledge of processes that underlie the stages, outcomes and activities of designing enabling problem finding and solving using a combination of synthesis and analysis is broadly categorised as *design thinking* and associated *development processes*, further discussed in the two subsequent sections. These processes need to be applied in all types of designing characterised by the other dimensions described above. Criteria represent the needs and aspirations of the stakeholders of design and the *Disciplines* of knowledge involved, the first major aspect influencing variations in designs and designing; this includes knowledge of society, technology, business and ecology, all of which are necessary for addressing issues of, among others, sustainability. Two major categories of disciplinary knowledge of technology are those of *engineering*, utility, or function (e.g. fuel efficiency of a car), and of emotion, human factors, or *form* (e.g. visual attractiveness of a car). Design community is often divided into engineering designers (ED) and form designers (FD), each being experts in one of these two major types of knowledge. A third category of knowledge type that is important in design is organisational, entrepreneurial or marketing knowledge (e.g. commercial viability of a car).

The second aspect is the part of the *Lifecycle* being designed: it can be a single phase (e.g. materials, manufacturing, etc.), a combination of phases (e.g. product-service systems), or the whole lifecycle. The third is the degree of *System* focus in the designing, i.e. whether the designer is involved in designing components (e.g. gears), sub-systems (e.g. gearboxes) or the entire system (cars). The fourth is whether the designer is *Application/Domain*-specific (e.g. mechanical designer; textile designer), or domain-neutral (generic).

The fifth is the focus on the *Innovation process*, i.e. the type of systems being innovated for: (portions of) products, processes, services or businesses. These five dimensions are integrated in Fig. 1, which imply the following: appropriate (parts of) *systems* and their *lifecycle* phases for the various elements within the *innovation* process are developed by drawing on knowledge of the specific *disciplines* in the *applications* of interest.

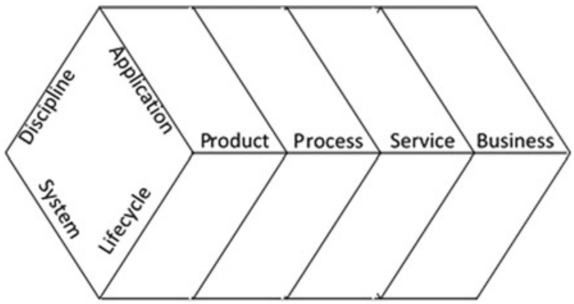

Fig. 1 Five aspects that broadly determine the variations in designs and designing

4 Evolution of the Idea of the Designer: A Historical Perspective

Designers in the beginning were 'practitioners of craft' of the early, pre-industrial production area, where functional, human and organisational aspects of a system were developed together organically, typically by individual crafts folk who operated within small ecosystems such as villages. As described by Ameri and Dutta [11], a village cobbler would handle the entire product lifecycle on his own. As industrial revolution ushered in the era of industrial, higher-volume production, functional, formal and organizational aspects became separated and handled by specialists in each.

In the UK, "formal design education emerged…in the wake of the industrial revolution as part of a reform directed at what were considered poor quality machine-made artefacts…This rethinking eventuated in apprenticeship models that were fueled by turn-of-the-20th Century zeal for the reform of society. The Central School of Arts and Crafts opened in London in 1896… as the result of a long-standing discussion about the poor standard of British manufacture and how industrialization had brought the decline of creativity and artisanship. The reference point was the Great Exhibition held at the Crystal Palace in 1851, which was regarded as a showcase for goods made around the world, and the poor quality of the British ones" [12].

Inspired by the Central School, a new form of designers was championed in Germany by Bauhaus (1919–1933) and Ulm (1953–1968) schools—shaping up the concepts of *form designers* and *industrial designers*, who would focus primarily on aesthetics, usability, meaning and other human factors in their designs. As described in Wikipedia [13], "…in general engineering focuses principally on functionality or utility of products, whereas industrial design focuses principally on aesthetic and user-interface aspects of products." The idea of Bauhaus was explained in its manifesto: "The main aim of all visual arts is to contribute to the integrity of the structure. In the past, the noblest function of the fine arts was to decorate the constructions…-Today, there is not a connection among the arts. Architectures, artists and sculptors have to learn the composite characteristic of the construction as a new concept. The artist is an artisan that has shifted his art to the higher level" [14]. In Bauhaus, education in form design was given…under three main fields of art: architecture, painting and sculpture, which consisted of three main stages: basic art education, vocational art education, and professional and project-based studies.

A specific, sometimes overlapping category [13] of industrial designers came to be called *'product designers'*, who focused on form-related attributes of three-dimensional products, and for whom applying knowledge of form to such a product, including development of their 3D models, became essential. Design education in institutions in India started with the adaptation and indigenization of the above views, in the creation, in 1960s, of the National Institute of Design (NID). This subsequently proliferated to and further adapted in various forms in the design education programmes at the Industrial Design Centre (now the IDC School of Design) at IIT Bombay (1970s), Department of Design at IIT Guwahati (1990s), Department of Design at IIT Hyderabad (2014), etc.

In the functional domain, growth of disciplines in engineering seemed to have had a longer tradition. According to Coyle [15], the first engineering school in Europe, Ecole des Ponts et Chaussées, was established in France in 1747, and by 1796 some lectures on the principles of engineering were already being delivered at the University of Cambridge in the UK. However, growth of engineering design as a discipline has been more recent, where engineering or '*function designers*' focused on developing various aspects of the artefact such as performance, maintainability, robustness, manufacturability, reliability, and so on. Engineering design was championed by a large section of the German-speaking schools of technical education, the earliest efforts being by "…Redtenbacher and Reuleaux who pioneered some of the earliest ideas on the principles of machine design in the 1850s. The first step-by-step approach was developed by Erkens in the 1920s. The concept of systematic design was stimulated in the 1950s and 1960s by Kesselring, Tschochner, Niemann, Matousek and Leyer," who "…identified the various phases and steps of the design process, and provided specific recommendations and guidelines for tackling them" [16].

Since the introduction of the book of Matousek in 1963 [16], engineering design grew steadily as a discipline, with extensive training being given today at departments of engineering design and product development in technical universities. In Germany, prominent ones are those at the Technical Universities of Munich, Darmstadt, Stuttgart, Karlsruhe and Berlin; in other parts of Europe major ones include DTU in Denmark, KTH in Sweden, NTNU in Norway, Tampere University of Technology in Finland, Politecnico di Milano in Italy, ETH Zurich in Switzerland, etc. In the USA, Mechanical Engineering at MIT, Stanford Centre for Design Research, and EDRC in Carnegie Mellon had championed engineering design education and research. In an attempt to strengthen engineering design research and education in the UK, a number of centres of excellence called Engineering Design Centres (EDC) were established in the early 1990s, at Universities of City, Cambridge, Strathclyde, Lancaster, Bath, Plymouth etc.; EDCs focused on the various functional aspects of design, from design synthesis to optimisation. In the 1990s, a centre of excellence called 'Research into Artifacts Centre for Engineering' (RACE) was established at University of Tokyo, Japan for a similar purpose.

According to [17], education in the area of organisation (or management), started with the initiation of "…the first purpose-built school of commerce called Escola do Comércio, founded after the 1755 Lisbon earthquake. Lisbon was then the center of the rich and powerful Portuguese empire, and the school was established to train public administrators to manage taxes and disbursements…The first university chairs in Administrative (Cameralist) Science were appointed in Germany in 1727 and in

Sweden in 1750. In Moscow, the Practical Academy opened in 1804; in Paris, the ESCP was founded in 1819 as a standalone school. Schools of commerce also were founded in Vienna and Budapest in 1856 and in Venice in 1868."

Frederick Taylor is often called the 'father of scientific management', who proposed by the late nineteenth century that organisations should study tasks and develop precise procedures [18]. His associate Henry Gantt developed the Gantt chart in 1910, and Frank and Lillian Gilbreth, a husband-wife team, introduced motion study. Later, Henry Fayol of France (1841–1925) initiated the modern theory of general and industrial management [19]. Today, management education uses systems theory as its broad underlying principle, with a proliferation of specialized areas such as operations, strategy, finance etc. taught at a variety of institutions and university departments. Prominent ones include Wharton School and Harvard Business School in the USA, Judge Institute of Management Studies in Cambridge, UK, and similar others in other parts of the world.

India's first business school, the 'Commercial School of Pacchiappa Charties' was established in Chennai in 1886. Indian Institute of Social Science founded in 1948 India's first management programme. Soon after, XLRI was initiated in the same year [20]. The Government of India established Indian Institutes of Management (IIM), first in Calcutta first and then in Ahmedabad, in 1961. As Shekhar Chaudhuri, a former director of IIM Kolkata, writes, "During the 1990s and 2000s the growth in the number of institutions providing management education continued unabated; in fact at a faster pace with the All India Council of Technical Education (AICTE) giving permission to set up such institutions in large numbers. This growth was fuelled by an unprecedented growth of the Indian economy during the last decade" [21].

Growth of each area (function, form and organisation) continued with the creation of more specializations, each getting further apart from one another as population, prosperity, complexity of consumer needs and aspirations, and the science and technology to support each grew, leading to emergence of multiple disciplines within each area.

Some of the enterprises involved in designing focus(ed) on sub-systems or components (e.g. resistors, transistors, PCBs, gearboxes) in various domains and applications; others focused on design of systems (e.g. audio systems, video systems, automobiles, etc.). Each happened both within disciplinary/application boundaries and outside; often multiple technologies from various functional and formal disciplines had to be brought together to develop such systems, which led to the emergence of educational programmes in multi-disciplinary domains, e.g. mechatronics (a combination of mechanical and electronic domains) [22], human computer interaction (a combination of human and computing domains), [23], and others.

Training, especially in the area of sustainable design, has undergone an expansion in both the system of focus and the criteria to be considered. According to Ceschin and Gaziulusoy [24], the area progressively expanded from a technical and product-centric focus towards large scale system level changes (Product, Product-Service System, Spatio-Social System, and Socio-Technical System) in which sustainability came to be seen as a socio-technical challenge. On the other hand, 'Design for

Environment (DfE)' or 'Ecodesign', which refers to design strategies that focus on improving the ecological aspects of a product, has expanded into, "Sustainable Design (SD), also known as 'Design for Sustainability' (DfS)…which expands on ecological considerations…by additionally taking into account economic and social considerations and aiming to generate solutions that consider the whole life cycle of the product" Sheldrik and Rahimifard [25].

Current approaches to design for sustainability, therefore, recommend developing the entire lifecycle of the systems being designed, from the processes of creation of materials, through those that turn these into products and systems, and those that take place during their usage, maintenance and repair, to those that comprise the phases that these systems undergo in their life after retirement. Designers variously embrace a specific phase such as product design, process design, service design, etc.; a combination of phases such as design of product-service systems where a product, its manufacturing and its services are all designed together; or all phases of the lifecycle, the most complete form prescribed for design for circular economy and sustainability.

As the ambit of work of a designer expanded in both functional and formal aspects, the concept of the industrial designer expanded further into that of the *'industrial design engineer'*, one who would develop both the functional and formal aspects of the system for the benefit of the society, and therefore had to be adept at multiple disciplines of engineering as well as multiple disciplines of form. This has been championed, among others, by the design school at Delft in the Netherlands and by the highly successful joint Masters' programmes in 'Industrial Design Engineering' run by Imperial College London and Royal College of Art in the UK. In India, training in this form of designers was initiated in the 1990s by the Centre for Product Design and Manufacturing (CPDM) at Indian Institute of Science (IISc); similar programmes have since been initiated at the Design Programme at IIT Kanpur (2002), Department of Engineering Design at IIT Madras (2006), Department of Design at IIITDM Jabalpur (2008), etc. Ability to develop both functional and formal aspects of a product is an essential competence for these designers, where knowledge from multiple disciplinary domains in each plays a major role.

Till the twenty-first century, however, organisational and business aspects were left largely out of design programmes, to be addressed primarily by business schools (as discussed before), who often spent greater parts of their curricula in training 'managers' for running established businesses in established organisations. The culture of 'startups', though present since the nineties, see Wikipedia [26], found universal acceptance only recently, and with it grew the idea of *'innovator-entrepreneur'*. This newest breed of designers must embrace everything needed to take their ideas to the market and the society. They would have to start with the aspirations and needs of, and problems in the society, and develop and implement all aspects of their innovation, including services and business, so that the innovation reaches, and is sustained within the society. Organisational knowledge is a critical element of the repertoire of knowledge for these designers, as is their knowledge of design thinking (an application-neutral design mindset) and a detailed process that are applied together for designing across domains.

A major champion of this view is Stanford University in the USA. Stanford is uniquely placed for this, given its proximity and closeness to the Californian Silicon Valley and its startup culture. The Masters' programme at Stanford entitled 'Design Impact Engineering' [27] is an example of a training programme that aims to develop such designers, where the courses offered expose students to a mix of form, function, entrepreneurial and social knowledge, which is then applied in the final year projects during which new solution ideas are taken all the way to the market. Being placed in Bangalore – the startup capital of India, the M.Des. programme at CPDM that had pioneered training students in India into becoming product design engineers has now evolved into a programme that trains students to become a multi-disciplinary innovator-entrepreneur.

5 Types of Designers

Analysis of the above history leads to at least six dominant views of the designer, as follows:

- *Craft Designer (CD)*, who develops all aspects of a craft, e.g. Toy designers in the Etikoppaka tradition of Andhra, using manual production techniques.
- *Engineering Designer (ED)*, who designs functional aspects of a product for industrial production (e.g. PCB designers, VLSI designers, etc.).
- *Form Designer (FD)*, who designs specific formal aspects of a product for industrial production (e.g. UI/UX designers, graphic designers, etc.).
- *Industrial/Product Designer (IPD)*, who designs all formal aspects of a system for industrial production (e.g. product designers who design semantic or aesthetic aspects of a car).
- *Industrial/Product Design Engineer (IPDE),* who designs both functional and formal aspects of a product system for industrial production. They are often 'bridge' designers, who play the role of systems integrators in an organisation, and often lead design in all aspects of the product within a start-up.
- *Innovator-entrepreneur (IE)*, who designs societal, formal, functional and organisational aspects of most or all parts of the lifecycle of the system being marketed as well as its implementation, spanning the entire innovation process for industrial production. Typically, innovator-entrepreneurs lead start-ups in innovative industrial products and systems.

Note that although these are found to be the dominant variants of the idea of the designer, the space created as a combination of the five dimensions in Fig. 1 leaves scope for many other types of designers to be conceived. For instance, a design school may train its students to become service and business designers, as championed by the Indian School of Design Innovation (ISDI) in Mumbai.

6 Types of 'Thinking' (Aspects of Design)

As discussed in [2], there are five areas of competence in which designers discussed above should be trained:

- *Innovation Thinking:* For those designers who need to lead innovation of products, processes, services and businesses, as a part of creating or developing new organisations.
- *Lifecycle thinking:* For those designers who need to be competent at identifying innovation opportunities at the various phases (material, production, usage, and/or after-use) of the lifecycle of the system being designed. They need to be able to design not just the product, but (subsets of) the whole lifecycle, thereby embracing sustainability.
- *Systems thinking:* Designers need to reason about their designs as systems that are part of larger systems so that these provide the benefits for which these are designed. Even for component designers, it is essential to appreciate how their components contribute to the larger systems of which these components are parts.
- *Design thinking:* Designers should be able to lead development of solutions that meet the needs and aspirations of the stakeholders. Critical to this are competence in empathy, synthesis, analysis, problem finding, problem solving, and learning through prototyping and 'fail-fast' iterations.
- *Inter-disciplinary thinking:* Designers often need to lead development of solutions that cut across disciplinary boundaries. This requires exposure to the interdisciplinary needs and aspirations of the stakeholders (criteria in the ACLODS framework), and the available technology building blocks from across domains that may have to be integrated in order to implement such solutions. Required knowledge encompass those of the society, ecology, economy and technology, where technology includes knowledge of domains including those of form (aesthetics, ergonomics, semantics, etc.) function (mechanical, electronic, computing, etc.), and organisation (entrepreneurship, marketing etc.).

The above areas of competence are important and complementary. Innovation thinking helps the designer to generate market and employment (innovator-entrepreneur); design thinking helps identify and address the right needs. Lifecycle thinking helps the designer address ecological, economic and social challenges that span across the lifecycle. Inter-disciplinary thinking enables tackling of complex problems that cannot be solved using knowledge within a disciplinary boundary. Systems thinking helps clarify how designs across various system boundaries must work together. Appendix 1 provides a categorisation of the areas in which each type of designers need to be trained.

7 Types of Knowledge Needed for Design

The above areas of competence can be inculcated, strengthened and supported by providing training with domain and process knowledge underlying each type of thinking, in four related forms, as discussed in [28]:

- *Thinking:* This is the application-neutral, basic innovation mindset for the designer.
- *Development Process:* This is the detailed design process that is variously specific to the domain of application, e.g. engineering design process, automobile design process, etc.
- *Domain Knowledge and Building Blocks:* These are the underlying knowledge and building blocks available in the various disciplinary domains of knowledge, be they human sciences, organisational sciences, engineering sciences or ecological sciences that underlie the functional, formal and organisational knowledge, e.g. structural mechanics, elements of design, trusses and beams, pull-down menus, Gantt charts, cultural motifs, etc.
- *Skills, Methods, Techniques and Tools:* These include the various forms of skills and support that make it easier, cheaper or faster to design systems, e.g. sketching skills, ideation methods such as brainstorming, analytical methods such as problem reformulation in 'Theory of Inventive Problem Solving' or TRIZ [29], tools for modelling or rendering, tablets for sketching, packages for finite element analysis, etc.

When the four forms of knowledge for the five types of thinking are laid out in a matrix (see Appendix 2), the matrix can be used to identify the comprehensive list of the types of knowledge needed in design. Each type of knowledge is described as a combination of the type of thinking and the form of knowledge—i.e. the cells in the matrix. Depending on the type of designer to be trained, one can now identify which of these knowledge-types would be of importance to that designer, as delineated in abbreviated forms within the cells in the matrix. Training in these types of knowledge must be complemented with innovation projects having open-ended problems, in which designers are able to apply a combination of these forms of knowledge in order to move through the stages of identifying problem as well as developing ideas, prototypes, associated production processes, services and business systems.

8 Design Education and Engineering Education

As discussed in [2], a major difference between technical and design schools in India is the polarisation in the nature of training, and in the disciplinary areas in which this training is provided. Particularly distinct is the division in the types of designers being created: while design schools often train students to become craft designers, form designers or industrial designers (all with strong components of training and skills in knowledge of form), technical schools typically train students to be single-discipline, engineering analysts.

In engineering education in India, connection to the society is almost entirely absent, as is exposure to multiple disciplines within even functional domains, and as to how knowledge from the multiple domains are to be integrated to solve problems to meet societal needs and aspirations. Majority of the design schools inculcate a synthesis oriented exploratory process of design, while technical schools train in analysis-oriented, deductive design processes. Further, in technical education, the focus is only on problem solving and not on problem finding, using analysis rather than synthesis; on design of components rather than systems, rarely embracing societal, formal or business aspects, and rarely designing associated manufacturing systems, services or businesses. This makes the resulting engineering graduates rather inadequate as systems designers, industrial design engineers or innovator-entrepreneurs.

In design schools, on the other hand, the excessive focus on human factors, relatively little focus on rigorous analysis, and little training on manufacturing, services or business aspects, make the resulting designers also inadequate in their training to embrace design as an industrial design engineer or an innovator-entrepreneur.

9 Need for Dedicated Departments/Expertise in Design in Engineering Education

Overall, there are two broad reasons as to why dedicated departments and expertise in design are needed in a faculty teaching in engineering schools:

- The first is to train engineering students to become *engineering designers*: This would require developing competence that is missing now but is necessary for the single-discipline engineers (e.g. mechanical engineers) to become better equipped as designers: competence in design thinking and processes; competence in problem finding and problem solving; competence at both analysis and synthesis; and training in working as multi-disciplinary engineering designers.
- The second is to impart training to create the *other types of designers*: form designers, industrial designers, industrial/product design engineers, or innovator-entrepreneurs, etc.

Appropriate elements of knowledge necessary for each of these purposes can be identified from Appendix 2, which can be used to guide targeted development of curricula for each such training programme. This also calls for research into development of tools and their validation, so that these can benefit designers in performing their roles in the various types.

Design departments should have faculty members that are drawn based on the areas of expertise needed in the elements of knowledge necessary for training the types of designers planned to be trained by the department. Since design is an 'inter-disciplinary discipline [1], it is inevitable that the faculty will be from multiple disciplines of form, function and/or organisation, as necessary.

Criteria for selection of candidates, where necessary for admission to degree programmes in design, should be based on the aptitude needed for the type of designers being trained for in the degree. If, for instance, the training is for form design, aptitude in formal elements along with aptitude for the various elements of the five types of thinking (e.g. design thinking comprising problem finding, problem solving, analysis, synthesis, etc.), as well as sensitivity to society, ecology etc., need to be tested.

If the intent is to train students to become engineering designers, aptitude for functional elements along with the rest above (sensitivity to society, ecology, etc. and the others listed in Appendix 2) should be the elements to be tested for.

In other words, it is the types of designers to be trained that guide the knowledge needed, which guide the types of faculty members needed for, and the types of tests needed for selection of appropriate students in the department.

10 Summary and Conclusions

This paper investigates the nature of design and innovation processes in all their nuances, in order to identify some of the dominant types of designers and their roles in the society. It then develops a theoretical basis for working out the elements of knowledge needed in the training for developing each such designer type. The aim is to support in a systematic manner the growth of design education, including those in the context of engineering education in India.

The main conclusion is as follows: the idea of the designer is evolving, and there are at least six, dominant, alternative meanings to the term 'designer'. In India, design schools seem to fall into two categories: those that champion the ideas of the designer as a craft designer, form designer or industrial/product designer, and those that champion the ideas of the designer as engineering designer, industrial/product design engineer or innovator-entrepreneur.

All of these six types are valid categories of the term 'designer', who must co-exist to support each other in the vast design and innovation ecosystem we inhabit. However, courses must be tuned appropriately to support training of each designer type. This paper proposes a scheme for determining the knowledge elements necessary for each such training.

Open-ended projects that involve both problem finding and solving, and both analysis and synthesis, all the way from developing products and processes to developing services and business, with implementation of outcomes e.g. developing, making and user-testing of working prototypes, as well as design of supply chains and businesses should be ideal test beds for bringing together the knowledge taught.

Further, it is necessary to initiate programmes for research into design and innovation so as to build the capability to develop knowledge with which to better the practice of design and innovation and its education can be better informed and supported. This calls for a plethora of new areas in which tools, including PLM tools, need to be developed.

In 2014, India Design Council proposed a 'design spine' [30] to be included as the design supplement in engineering education. It proposes to do by including courses in "…industrial design and design thinking and not expressed as engineering design". It is necessary, however, that the specifics of any such proposals be evaluated on the basis of the type of designers intended to be trained in a school of engineering education, which should determine the elements of knowledge essential to be inculcated in each such training.

If, for instance, the training is intended to help develop current engineering scientists (as typically produced in engineering education in India) into engineering designers, it is crucial to develop multi-disciplinary thinking, including synthesis and analysis that link societal elements of knowledge with knowledge from relevant, multiple disciplines of functional technology. This is crucial for developing the competence for designing multi-disciplinary functional systems (see in Appendix 2 the elements of knowledge necessary for development of engineering designers), which requires, as part of the training needed, honing not only thinking but also associated processes, building blocks, skills, methods and tools. Any 'design spine' must therefore include training in engineering design synthesis, which is normally completely missing in engineering education in India.

If the intent of the training is to develop students into any of the other types of designers, the elements of knowledge in the training must be accordingly modified. It is important, in general, to inculcate a balanced programme for training with thinking, process, building blocks and skills/methods/tools that utilize functional, formal as well as organisational aspects of technology that are relevant for multi-disciplinary design of lifecycles of systems across multiple applications and multiple areas of innovation.

Future work into further expanding the framework proposed includes carrying out more detailed studies of applying the framework in the various curricular settings in engineering and design schools, and seeking further validation and detailing of the framework.

Appendix 1: Types of Designers and Aspects of Design in Which They are involved (So: Society; El: Ecology; En: Economy; Te: Technology; Fo: Form; Fu: Function; Or: Organisation; Cp: Components; Sy: System; Mt: Materials; Mf: Manufacturing; Us: Use; Re: Retirement; Sp: Specific; Ge: Generic; Pr: Product; Ps: Process of Implementation; Se: Service; Bu: Business)

	Discipline						Systems		Lifecycle				Appl-domain		Innovation Process			
	So	En	El	Te			Co	Sy	Mt	Mf	Us	Re	Sp	Ge	Pr	Ps	Se	Bu
				Fo	Fu	Or												
Craft Designer (CD)	*		*	*	*		*	*	*	*	*		*		*			
Engineering/Function/Utility Designer (ED)	*		*		*		*	*		*	*		*	*	*	*		
Form/Emotion Designer (FD)	*		*	*			*	*			*		*		*			
Industrial/Product Designer (IPD)	*		*	*				*			*		*	*	*			
Industrial/Product Design Engineer (IDE)	*	*	*	*	*		*	*		*	*		*	*	*			
Innovator-Entrepreneur (IE)	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*

Appendix 2: Types of Knowledge Needed for Various Types of Designers in the Various Aspects of Design (CD: Craft Designer; ED: Engineering Designer; FD: Form Designer; IPD: Industrial/Product Designer; IDE: Industrial/Product Design Engineer; IE: Innovator-Entrepreneur)

	Discipline						Systems		Lifecycle				Appl		Innovation Process			
	So	En	El	Te			Co	Sy	Mt	Mf	Us	Re	Sp	Ge	Pr	Ps	Se	Bu
				Fo	Fu	Or												
Thinking (Mindset)	CD ED FD IPD IDE IE	IDE IE	CD ED FD IPD IDE IE	CD FD IPD IDE IE	CD ED IDE IE	IE	CD ED FD IDE IE	CD ED FD IPD IDE IE	CD IE	CD ED IDE IE	CD ED FD IPD IDE IE	IE	CD ED FD IPD IDE IE	ED IPD IDE IE	CD ED FD IPD IDE IE	ED IE	IE	IE
Development process	CD ED FD IPD IDE IE	IDE IE	CD ED FD IPD IDE IE	CD FD IPD IDE IE	CD ED IDE IE	IE	CD ED FD IDE IE	CD ED FD IPD IDE IE	CD IE	CD ED IDE IE	CD ED FD IPD IDE IE	IE	CD ED FD IPD IDE IE	ED IPD IDE IE	CD ED FD IPD IDE IE	ED IE	IE	IE
Domain knowledge/ building blocks	CD ED FD IPD IDE IE	IDE IE	CD ED FD IPD IDE IE	CD FD IPD IDE IE	CD ED IDE IE	IE	CD ED FD IDE IE	CD ED FD IPD IDE IE	CD IE	CD ED IDE IE	CD ED FD IPD IDE IE	IE	CD ED FD IPD IDE IE	ED IPD IDE IE	CD ED FD IPD IDE IE	ED IE	IE	IE
Skills/ Methods/ techniques/ tools	CD ED FD IPD IDE IE	IDE IE	CD ED FD IPD IDE IE	CD FD IPD IDE IE	CD ED IDE IE	IE	CD ED FD IDE IE	CD ED FD IPD IDE IE	CD IE	CD ED IDE IE	CD ED FD IPD IDE IE	IE	CD ED FD IPD IDE IE	ED IPD IDE IE	CD ED FD IPD IDE IE	ED IE	IE	IE

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Supply Chains

A Study on Impact of Industry 4.0 on Supply Chain Efficiency Among Manufacturing Firms

R. Sujitha, B. Uma Maheswari, and L. Ivan Kenny Raj

1 Introduction

The Industrial revolution initiated way back in 1760s paved way for the first major breakthrough in manufacturing which shifted the focus from agriculture to manufacturing during this phase. Industry 1.0 initiated the concept of manufacturing using machines which not only improved the scale of operations but also the efficiency, enabling small businesses to cater to a larger customer base. This was possible due to mechanization fuelled by steam and coal. Industry 2.0 started in the nineteenth century was more technologically advanced with the focus being on electrical energy. Automation of assembly line operations in mass production created more job opportunities. Industry 3.0 came into force during the twentieth century. This phase witnessed the dominance of electronics, integrated circuits and advancements in hardware and software. It also saw progressive integration of technology in various aspects of manufacturing including inventory management, logistics, supply chain and enterprise resource planning [28]. Industry 4.0 saw rapid advancements in the field of information technology, internet and telecommunication technology. This period witnessed the evolution of internet of things, embedded software, cloud computing etc. [8].When the industrial revolution unfolded, the industry's supply chain also progressed to improve and keep pace with the changing facets of the industry.

Industry 4.0 and its accompanying technologies have the potential to impact every aspect of factories and businesses, and can significantly improve all managerial disciplines, including supply chain and logistics management. Supply chain management is a set of steps that begin with marketing, product development, manufacturing,

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and distribution, and end with the client receiving the goods. Collaboration between all the stakeholders in the supply chain is very important in order to improve the efficiency of the process. The constant rise in business system automation, as well as the accompanying efficiency and productivity gains and quality improvements, is prompting companies to apply Industry 4.0 operating principles to other aspects of their businesses, such as supply chain management. Because the supply chain is so intertwined with the industry, it is critical to keep a careful eye on how changes in the sector affect it. The digitalization, integration of robotics, and Internet of Things (IoT) in the logistics framework are referred to as supply chain 4.0. Given the rising importance of technology in business operations, the goal of this study is to explore the influence of technical advances connected with Industry 4.0 on supply chain performance through an empirical analysis. It is also very critical to understand the impact of these new developments on the supply chain efficiency and this study is an attempt in that direction. The study would set the direction for more detailed research in this domain in the future.

2 Literature Review and Research Framework

Industry 4.0 involves implementation of new technologies in an organization which leads to process efficiency in the industry and in turn economic development of the country. It represents rapid advancements in terms of data handling coupled with disruptive innovation in hardware and software [24]. The implementation of Industry 4.0 involves digitalizing the process in an organization in order to derive more insights with an aim of improving operational efficiency. This in turn leads to more transparency within an organization thus creating more value at all stages of the production process. It is about how advancements in the field of technology decentralizes the various aspects of the business. It is also about creating a culture of connectivity among not just employees but also the systems, processes and machines in an organization. The pandemic has drastically impacted all industries and their supply chain [26]. Therefore there is a need to focus on supply chain strategy, supply chain orientation, inter-organizational collaboration, human centric issues and customer value creation [7]. There are also many barriers in implementing Industry 4.0 including the lack of awareness and fear of implementation new technologies. Factors associated with the budget involved and the technical difficulties in data integration and human robot work collaboration also prevents the implementation of Industry 4.0. The management plays a key role in the resolution of problems relating to implementation of Industry 4.0 [2].

Supply chain performance is based on various measures. The order fulfilment rate is one such measure used to assess supply chain performance. This metric encompasses crucial factors such as order input, activity scheduling, and tracking. When companies interact with their customers, it is possible for them to respond to their needs in a timely and efficient manner, boosting order fulfilment and visibility. The efficiencies provided by the materials management process benefit a well-managed supply chain. The company can meet the expectations of consumer orders in a timely manner. Connecting assembly processes with the network of logistics providers that run direct material delivery facilities is critical. Suppliers will need to keep inventory buffers in vendor-managed storage facilities to guarantee that crucial components are not in short supply. For timely delivery of goods and improved customer service, an effective logistics-information management system is essential. Consumer response connects logistics to the customer base on the outside and sales and marketing on the inside.

An effective customer service policy that yields the lowest cost of missed sales, inventory carrying, and distribution is developed and implemented, customer reaction is optimized. It is critical to reduce the time it takes from the time an order is placed to the time it is received by the customer. Simultaneously, it is critical to track the shipment and minimize shipping faults. Finally, client concerns should be closely monitored. An effective supply chain should be able to respond to and accommodate demand variations such as seasonality, as well as accommodate and respond to periods of poor supplier performance, poor manufacturing performance such as machine breakdown, poor delivery performance, and the introduction of new products, markets, or competitors.

Implementation of IoT technology in the organization would impact supply chain process flow and management [19]. Automated tracking systems, simplified processes and efficient supply chain system would be possible with IoT [1]. Integrating IoT technologies in the industry will increase the safety performance in the industry and will result in the free flow of the supply chain process [17]. The study focused on the safety and productivity aspects in implementing IoT in industry 4.0 found that the implementation of IoT technologies in the supply chain will not change the entire supply chain of the industry, but have some positive impacts in safety, process efficiency and customer satisfaction [3]. IoT collaborated framework will increase the productivity and reduce the problems arising due to traditional methodology and also gives more accurate results [23]. Therefore the hypothesis proposed is.

H1: IoT implementation positively influences supply chain efficiency.

Industry 4.0 focusses on integrating robotics technology to improve productivity [12] and plays a key role in influencing the operational aspects of an organization and improves the process efficiency of the organization [9]. The safety aspects of the work environment and productivity are two major factors to be considered while implementation of robotics in the industry. In this scenario of human—robot collaboration, ethical issues of the workforce is bound to crop up. However, with an improvement in the skill level of the employees it is possible to solve the issues arising during such circumstances. The implementation of robotics in industries reduces the processing time [11] and the cost of production [14] by facilitating process integration. Collaborative robotics involves either full or partial automation of the task [16] leading to improved efficiency. This leads to increase in the accuracy of the work and reduction in the error rate as robots are capable of working for a longer period of time with minimal chances of error. The output generated by robots produced greater accuracy compared to the conventional process [10]. An analysis of the cost proves that the labor charges included in the conventional process can be substantially reduced by implementation of robotics in industries. Therefore, the implementation of robotics will have greater impact on the supply chain of an industry through improvement in the performance level. Therefore the hypothesis proposed is based on the above cited literature, the following hypothesis has been framed.

H2: Robotic working environment positively influences supply chain efficiency.
Implementation of Enterprise resource planning software in large scale organizations would be useful for the integration of data [21]. Real time analysis of data through data integration leads not only to smart logistics, but ultimately creates smart factories. However, the fear of implementing new technologies and the setup cost are the major barriers in introducing e-production, e-supply chain, and e-customer service. Studies show that proper data integration in large scale organizations would improve the supply chain flow. Providing proper training to the employees with new technologies would improve the performance of the workers and they will be capable to solve the issues arising due to the implementation of new technologies. Data integrity can be achieved in supply chain through the implementation of Cyber-physical systems (CPS) in organizations. CPS refers to the seamless integration of advanced technological applications in various domains of the organization. The information sharing and overall surveillance is easier when there is an IoT integration. Therefore the hypothesis proposed is.

H3: Data Integrity will have an impact on the supply chain efficiency.
Review of the literature indicates that the technologies like IoT implementation, robotic working environment, data integrity through the cyber physical system perform a critical role in impacting the supply chain of the organization. Hence a frame work is proposed for this research work to understand the influence of industry 4.0 practices on supply chain efficiency. The research framework is made up of four constructs derived from extensive review of literature (Fig. 1).

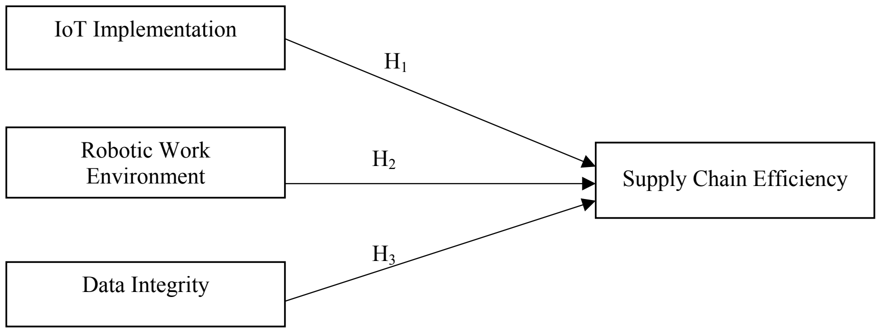

Fig. 1 Research framework

3 Methodology

3.1 Questionnaire

This study used a structured questionnaire that was developed based on the thorough literature review, for getting the responses. The main focus of the research was to study the Industry 4.0 practices and its impact on supply chain efficiency. The questionnaire was constructed using five-point likert scale, where 1 represented ‘strongly disagree’ and 5 represented ‘strongly agree’. The questionnaire had three sections, the first section captured general information about the participants and the second section measured the independent variables such as robotic working environment, data integrity and IoT implementation. The third section measured the dependent variable supply chain efficiency. Table 1 provides the explanation of the constructs and number of measurement items for each construct.

3.2 Data

This descriptive study was conducted among the manufacturing organizations in Tamil Nadu state in India. The manufacturing sector is one of the growing sectors in the state and contributes to the states’ gross domestic product output. There are many small and medium industries and a large manufacturing firms covering manufacture of tools and equipment, machinery and components, automobiles, basic metal parts and alloys, metallic products and repair of main capital products. The questionnaire was sent to managers in these firms who are working in firm for at least 2 years, so that they have sound knowledge about the firm’s practices and are familiar with Industry 4.0 standards. After the questionnaire was circulated, regular follow ups were done. As a result, a total of 122 responses were received and used for analysis.

Table 1 Definition of constructs and measurement items

Constructs	Definition	Questionnaire items
IoT implementation	The extent to which Internet of Things is implemented to track the materials and work practices	7 questionnaire items
Robotic working environment	The extent to which robots are used in routine work practices along with employees	7 questionnaire items
Data integrity	The extent to which the data is captured and assured of consistency and accuracy	7 questionnaire items
Supply chain efficiency	The extent to which the firms are able to utilize resources in the best possible way to respond to customers’ requirements and manage demand	12 questionnaire items

3.3 Analysis Criteria

WarpPLS, a software with graphical user interface was used to perform data analysis and Structural Equation Modelling. The path analysis technique allows to use a set of indicates to measure the relationship [27] between the latent constructs of IoT implementation, robotic working environment, data integrity and supply chain efficiency. The hypotheses of the study were accepted or rejected based on the p-value of the results.

4 Data Analysis and Results

4.1 Reliability and Validity of the Constructs

Cronbach's alpha was used to measure the reliability of the constructs. Cronbach's alpha, is a messure to check for internal consistency of the measurement items. It was developed by Lee Cronbach in 1951 to measure how closely the questionnaire items are related to each other and measure the latent variables. Alpha value greater than 0.7 is considered to be an acceptable value for the construct to be reliable [22]. The cronbach alpha value of the construct IoT Implementation is 0.802, Robotic Work Environment is 0.825, Data Integrity is 0.889 and Supply Chain Efficiency is 0.902. All the constructs had value cronbach's value greater than 0.7 indicating a sound reliability. Composite reliability is used for measuring the internal consistency of the questionnaire items [20]. The composite reliability values should be more than 0.7 for the measurement items to be inter-item consistent. The composite reliability of all the constructs are more than 0.7 indicating good reliability. The convergent validity of each construct is checked by examining the "Average Variance Extracted (AVE)" values and their correlation coefficients with the other latent constructs. AVE "assesses the amount of variance captured by a set of items in a scale relative to measurement error" [20]. AVE values of the constructs that are more than 0.5 are said to possess convergent validity [4]. AVE > 0.45 is recommended for scales that are developed new and values > 0.50 are required for other scales [15]. The composite reliability and Average Variance Extracted (AVE) of the constructs are shown in Table 2. The AVE values for all the constructs are greater than 0.5 representing convergent

Table 2 Reliability and AVE values

Construct	Composite reliability	AVE	Cronbach Alpha
IoT implementation	0.801	0.532	0.802
Robotic work environment	0.872	0.618	0.825
Data integrity	0.862	0.599	0.889
Supply chain efficiency	0.903	0.648	0.902

validity [4]. This reiterates that constructs are unidimensional [6]. The flowchart of the methodology and the corresponding statistical methods is given in Fig. 2.

Squares of correlations among the constructs were calculated and compared with AVE values. The squares of the correlations among the constructs were less than the AVE values showing good discriminant validity of the questionnaire items [15]. So the questionnaire was not refined further and the instruments was used for collecting data from the respondents of the study. The correlations among the independent variables and the square roots of AVEs are shown in Table 3.

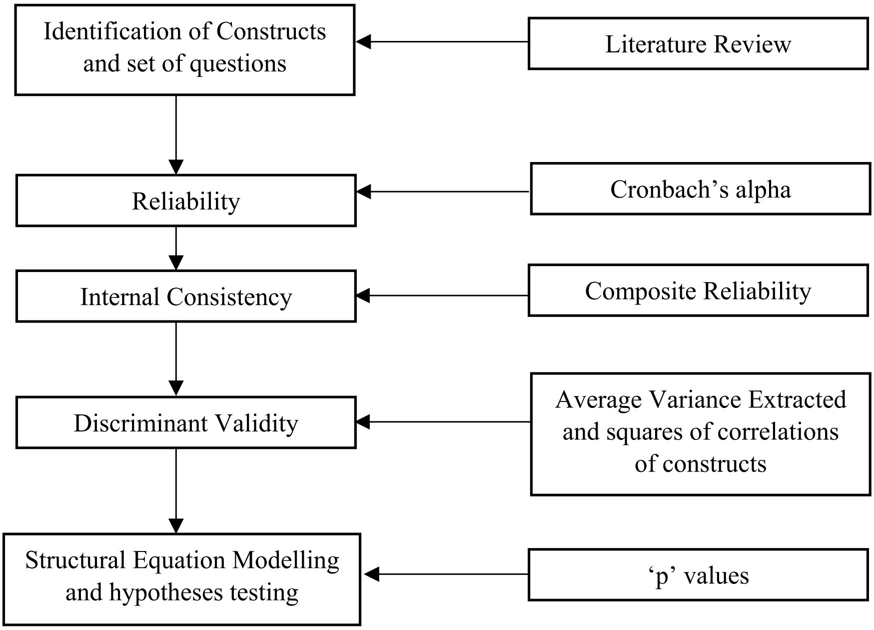

Fig. 2 Methodology flowchart

Table 3 Correlations among independent variables with square roots of AVEs

	IoT implementation	Robotic work environment	Data integrity	Supply chain efficiency
IoT implementation	(0.729)[a]	0.365	0.451	0.329
Robotic work environment	0.365	(0.786)[a]	0.267	0.307
Data integrity	0.451	0.267	(0.773)[a]	0.214
Supply chain efficiency	0.329	0.307	0.214	(0.804)[a]

[a] Square root of AVE values of the constructs

4.2 Research Findings

To understand the practices of industry 4.0 and supply chain efficiency among the organizations considered for the study, the average values of the four constructed were calculated. The average scores are given in Table 4. The analysis shows that the average scores of the measurement scales of all four variables are more than four. This shows a strong existence of Industry 4.0 practices and supply chain efficiency among the firms. Robotic work environment mean value scores 4.49, indicating that the robotic work environment exits and employees are willing to utilize them to improve supply chain efficiency. Data integrity construct scored a mean value of 4.56, indicating that data integrity through cyber-physical system will enhance the timeliness of raw material availability and delivery time of finished goods. IoT implementation scored 4.59 mean value, indicating that IoT enhances material tracking and eco-friendly working environment and firms have IoT implementation in place to improve their practices. Supply chain efficiency has a mean value of 4.57, indicating that supply chain practices are better practiced and the firms are having better order fulfilment rate, on time deliveries and reduced manufacturing lead time and customer complaints.

A structural equation modelling was performed to understand the relationship among the predictor and target variables at the aggregate level. Structural equation modelling (SEM) is a multivariate technique that is used for testing hypothesis. It is structural model which represents the hypothesis as a causal relationship among the variables [18]. The advantage of this model is that it minimizes the difference between the observed covariance structure and the covariance that is inferred by the structural model [5]. This path analysis method used multiple measures that develops a model to fit the dataset and allows testing of interrelations between the latent variables [25].

The Fig. 3 shows the output of the structural equation model. In the SEM model, β is the beta coefficient which is the corresponding change in the dependent variable for the degree of change in the independent variable. The path coefficients of all the constructs were found to be statistically significant. The relationship between IoT implementation at the organization and supply chain efficiency is significant ($\beta = 0.49$ and $p < 0.01$ is less than 0.05 level of significance) and this study supports hypothesis H1. This indicates a positive relationship between the variables and imposes that IoT implementation influences the firms' supply chain efficiency. The relationship between robotic work environment and supply chain efficiency is significant ($\beta = 0.20$ and $p = 0.01$ is less than 0.05 level of significance) and hypothesis H2

Table 4 Mean values of constructs

Constructs	Overall mean
IoT implementation	4.590319
Robotic work environment	4.49941
Data integrity	4.564345
Supply chain efficiency	4.576446

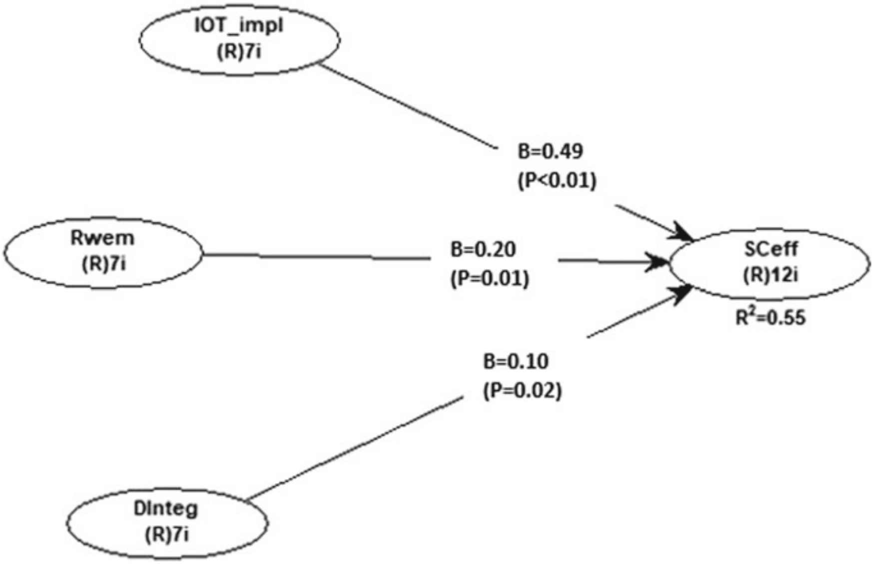

Fig. 3 Validated model

is supported. Also data integrity and supply chain efficiency was also found to be significant (β = 0.10 and p = 0.02 is less than 0.05 level of significance) and hypothesis H3 is supported with positive impact. The overall R-square of the model is 0.55, which shows that 55% variation in supply chain efficiency is due to industry 4.0 practices such as IoT implementation, robotic work environment and data integrity in the manufacturing firms. The R-square value indicates that the model is fit and the correlation is high between the predictor variables and the dependent variable. It is rational to conclude that industry 4.0 practices significantly impacts the supply chain efficiency.

5 Discussions and Implications

This study provides enough evidence that industry 4.0 practices are implemented in the manufacturing firms and that they are benefitted by increased efficiency in their supply chain management. The validated model in Fig. 2 indicates that the industry 4.0 practices drive the supply chain efficiency. The findings of the study reiterates the previous studies [13, 14, 24]. Robotic Working Environment positively influences supply chain efficiency because of reduction in labour hours and improved production rates at the organization. The robotic working environment would fail if there is more conflicts within human and robots. The results show that there are not human–robot conflicts in organizations and the risks and hazards are less for human beings in a working robotic environment that supports the supply chain efficiency. The human robot conflicts can be prevented in the Industry 4.0 by implementing COBOTS (i.e. Collaborative Robots) which will be the future for Industry revolution also it helps managers to handle less conflicts in the organization.

Data integration through the Cyber Physical System improves the supply chain efficiency of the organization. This is due high worker cooperation and timeliness of updating the data used in organization. The cyber physical system enhances the information flow which is the key mandate for supply chain efficiency and performance. Also data integration in the cyber physical system ensure a steady flow of materials in the supply chain, increasing its efficiency. IoT implementation has a positive impact on supply chain efficiency because goods safety is monitored thoroughly through IoT implementation. Managing and scheduling of goods can also be done efficiently through the IoT implementation in the organization. Tracking of materials can be done with high precision through the IoT implementation. It will improve the safety by reducing the hazards and risks in the working environment. Accidents can be prevented by this implementation of IoT and it makes the production flow obstacle less and thus improve the supply chain. Therefore, IoT used in production units improves the supply chain efficiency further.

In the field of Industry 4.0 and supply chain, the current study provides a theoretical as well as a practical foundation for operational excellence challenges. In the era Industry 4.0, this paradigm can also be used to compare, rank, and analyse coordination concerns in various supply chain activities in an organization. Organizations can use this strategy for benchmarking and to enhance various supply chain operations in order to meet changing market demands. These findings add to the continuing discussion about how digital technologies interact with dynamic supply chain capabilities to help companies gain a competitive advantage. These findings are important for decision-makers because they highlight the necessity for organisational changes beyond the mere implementation of Industry 4.0 technologies in order to properly benefit from them. This could also point to future study directions in this area.

6 Conclusion and Scope for Future Research

Industry 4.0 is going to be the future of all Indian manufacturing firms. Industries that resist adapting such technologies will fail in future. The industries are forced to adopt this upcoming technology to develop their markets and to make the supply chain more agile in nature. Industry 4.0 technologies does not change the entire supply chain system instead, it will be support the supply chain efficiency. Future industrial revolution will include both human being and robots working together, thus human resource managers should be capable of handling the conflicts in the industry. To conclude, supply chain efficiency can be improved only through the proper usage of the technologies in the way that will improve the performance and productivity. So, in order to survive in the competitive market and improving the supply chain efficiency, industries in India should implement Industry 4.0 technologies to ensure good supply chain management practices. If industries adapt these technologies, the process flow will be obstacle free and there will be seamless flow of information across all the entities in the supply chain. This would also help the firms to reduce the lead-time in production of goods.

Many companies in India who are trying to implement Industry 4.0 can use this research to develop their Industry for future benefit. In addition, future researcher who aim to do research on improvements to convert into Industry 5.0 can use this research. This research also gives future scope to the managers to do researches on impact on supply chain efficiency other technologies of industry 4.0.

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A Literature Review Based Bibliometric Analysis of Supply Chain Analytics

Anand Jaiswal and Cherian Samuel

1 Introduction

The use of analytics and advance data sciences has become essential for any organization to improve operational efficiency and productivity for competitive benefits [1]. Almost all the management streams that include production and operations management, sales management, marketing management, supply chain management (SCM), financial management, human resource management, and information technology management of an organization are using the approaches and tools of business analytics for optimizing the work efficiency and outcomes of the organization [2, 3]. Among all the management areas, supply chain management is a crucial area that directly impacts the performance of an organization. Any improvement in supply chain (SC) activities considerably enhances the organization's productivity and profitability, and supplements the interlinked supply chains of related organizations [4]. Because of it, research work based on the use of SC analytics in organizations is evolving with substantial swiftness. Various tools and processes of data analytics, business intelligence, expert systems, and qualitative and quantitative techniques are being developed and applied across multiple core domains of SCM. Research explorations are continuing in the SC analytics areas to improve the precision of supply chain decisions in planning, procurement, manufacturing, packaging, transportation, and after-sales management of an organization's products [5–8]. Because of a good focus on research ideas and academic works in and around SC analytics in recent times, there also arises a need for a systematic review of the literature to understand the research progression. Also, an estimation of research trends in SC analytics is

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required to understand the scope of future research work in the analytics and supply chain domain.

This paper attempts to provide a brief review of supply chain analytics outlining the challenges associated with SCM activities and the role of SC analytics. This paper briefly defines the basics of SC analytics and its functionality in accordance with the supply chain operations reference (SCOR) model. Further, the paper provides a short bibliographic study focusing on the last ten years (2010–2020) of research literature following the SCOPUS database. The paper will significantly contribute to the existing research literature of SC analytics. The research insights provided in this paper may aid academicians and researchers working in SC analytics areas to assess the research trends and key SC analytics areas for exploration.

2 Challenges Associated with Supply Chain Management

The supply chain of a product or service can be understood as a network of entities involved in the upward and downward flow of materials, machines, processes, finances, and information [9–11]. The management of activities across these supply chain entities is termed as supply chain management [12]. A similar definition of SCM is given by Stadtler in 2005, in which he referred to supply chain management as an upstream and downstream linkage of various organizations to manage processes and activities to add value in the product or services to meet the customer requirement [13]. So, the most critical issues associated with supply chain management are planning and designing the supply chain activities according to the needs of the consumers. Some other key issues related to supply chain management are (a) Competitiveness with the global market, (b) Selection of supply chain entities, (c) Optimization of network of organizations, (d) Process orientation and optimizations, (e) Technology challenges, (f) Minimization of production and delivery cost, and (g) Proper return management, [12, 13]. These issues raise the basic business challenges of how to meet the customer's satisfaction, how to optimize the process and flow of material, finance, and information within the supply chain, how to minimize the cost of production and delivery, and how to increase the profitability of the organization while maintaining the quality of product or services. Besides these challenges, several intermediate risks are also associated with the SCM, which poses a significant threat to the efficiency of the SC and the overall organization's performance [14]. These risks associated with SCM includes • cancellation or change of orders from the consumer side, • unavailability of workers, • machine or technological failure, • conflicting obligations from suppliers or other supply chain entities, • improper communications within SC entities, and various others [14, 15]. To manage these challenges and risks associated with SCM, there are several SCM processes over which SC analytics is used to observe, control, and improve the processes for optimized outcomes. Figure 1 shows a SC framework of an organization representing challenges and SCM processes. The following section discusses the role of SC analytics over these SCM processes.

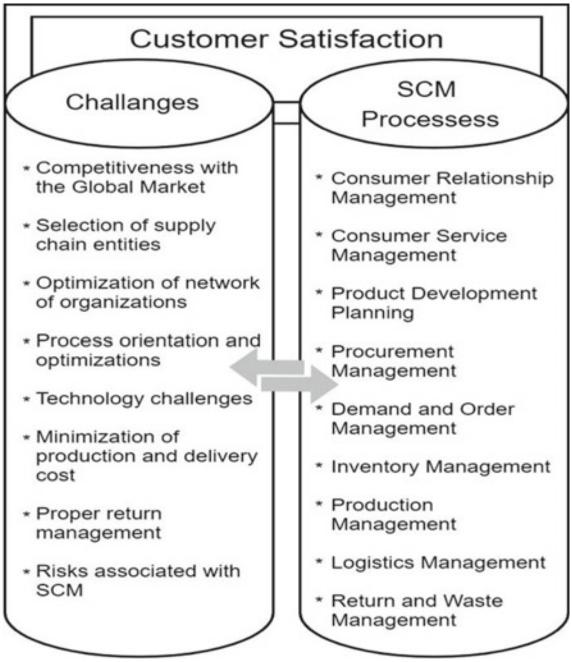

Fig. 1 Supply chain framework for challenges and SC processes

3 Role of Analytics in Supply Chain Management

The role of SC analytics is to use the data-driven analytical tools to incorporate business intelligence into different processes of SCM to make optimal decisions in the flow of materials, information, and finances within the supply chain [11]. To meet the global competitiveness and the customer's demand, organizations induce analytical supply chain models that focus on reducing the cost and time of production and delivery. Because of it, the traditional supply chain converts into an integrated supply chain with business intelligence [16]. Supply chain integration can be considered as a multi-network business strategy to bring all the supply chain entities in synchronization with a common goal of improved response time, reduced production time with minimum costs, and waste generated in the overall value-added flow of materials [17, 18]. With the use of analytics and business intelligence tools, this transformation of supply chain occurs smoothly, addressing the challenges of business processes integration while meeting the strategic business objectives in accordance with the newly integrated supply chain processes. Optimally planned and executed decisions based on knowledge processing through SC analytics directly contribute to the bottom line of the integrated supply chain. SC analytics plays a significant role in substantially reducing procurement, transportation, inventory, and waste management costs within the supply chain while meeting the time and quality constraints [11].

With the use of SC analytics in the planning stage, organizations analyze the data of prospected customer's interests and purchasing patterns to develop a demand forecast model to predict the future demand of a product or service [19]. This demand forecast constitutes the basis of all other procurement, production, inventory, and logistics planning activities in the supply chain [20]. The use of SC analytics in the planning stage of SCM also helps to estimate the implementation gaps and the necessary arrangements required to meet these planning-to-execution gaps [21]. In the planning stage of SCM, SC analytics provides crucial information such as demand, production scheduling, inventory capabilities, delivery time, and various other details, which significantly helps activities of different stages of the supply chain [19, 20]. The procurement phase of SCM utilizes these data generated through SC analytics to assess the production requirements and, accordingly, the quality and quantity of raw materials required from the suppliers [22]. There is an adequate number of research articles available focusing on SC analytics for supplier selection and other decision-making approaches in the procurement process. The use of SC analytics is also a surplus in the production phase of SCM. Most of the production planning and scheduling decisions are based on the information from the data provided by SC analytics from the planning phase. SC analytics enables the decision-makers to optimize the production process by optimal capacity management, materials management, production scheduling, and sequencing of processes [23, 24]. With the concerns of logistics management also, organizations use SC analytics to find ways to mitigate the complex challenges associated with distribution and transportations. SC analytics aids in identifying correct transportation plans, distribution network, delivery lot size, vehicle routing, vehicle type, and cost and time-efficient delivery of goods [25–28].

On an all, SC analytics finds its practicability and applications in all the supply chain operation reference (SCOR) model phases. The well-known SCOR model was developed by the Supply Chain Council (SCC), which is a reputed non-profit organization that focuses on outlining essential processes of supply chain networks [29]. The SCOR model defines the five main supply chain management domains: 'plan,' 'source,' 'make,' 'deliver,' and 'return.' All the SCM processes, as described in Fig. 1, are incorporated with the SCOR model, and the role of SC analytics is functional over each of the management practices of the supply chain.

The role of SC analytics in the 'plan' phase includes demand forecasting, performance measurement of the supply chain, product development planning, inventory control, and capacity requirement planning. Several supply chain processes are associated with the planning phase of the SCOR model on which SC analytics are implemented for optimal planning and assessment [19–22]. These supply chain processes include consumer relationships management, consumer service management, product planning, demand and order management, and inventory management [12, 15]. In the 'source' phase of the SCOR model, the role of SC analytics revolves around supplier selection analytics, supplier performance evaluation, procurement plan, and spend analysis for sourcing materials and services [30–32]. The supply chain process of procurement management is associated with the 'source' phase of the SCOR model [12, 15]. The 'make' phase of the SCOR model is associated

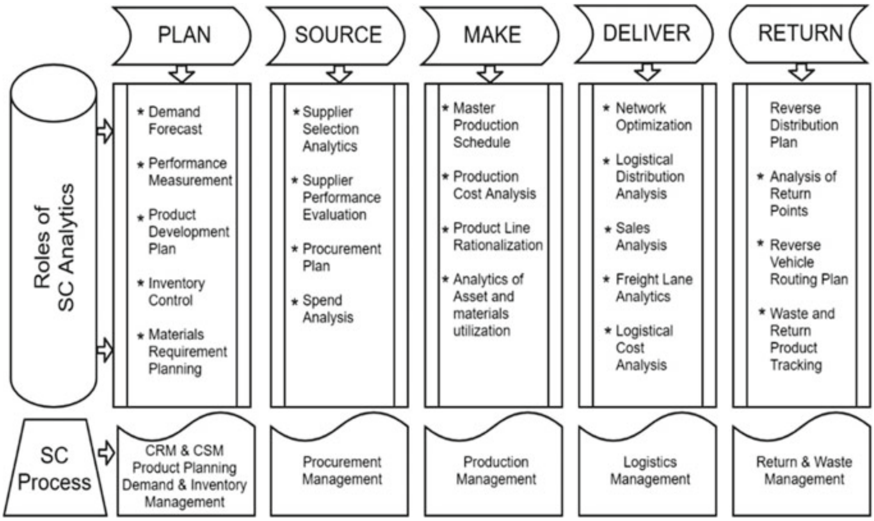

Fig. 2 A framework of SC analytics role in the SCOR model

with the production management process of SCM in which SC analytics is implemented for master production schedule, manufacturing cost analysis, product line rationalization, analysis of facility, materials, and asset utilization during production processes [23, 24, 33, 34]. Implementation of SC analytics in the 'delivery' phase of the SCOR model works on supply chain network optimization, logistical distribution analysis, sales analysis, freight lane analysis, transportation, and delivery cost assessments [27, 28]. In the 'return' phase of the SCOR model, SC analytics is utilized for reverse distribution plan, analysis of return points, reverse vehicle routing plan, and efficient waste and return product tracking [35]. The 'deliver' and 'return' phase of the SCOR model is managed in logistics management and return and waste management processes of SCM, respectively. The framework of the SC analytics role in the SCOR model is provided in Fig. 2.

4 Bibliometric Study of SC Analytics

In this section of the paper, a bibliometric study of SC analytics is provided. The research papers selected in the study are from the research literature published in the last ten years (2010–2020). In identifying the articles, dissertations, books, book chapters, conference proceedings, web and press articles, and blogs were avoided for the qualitative insights and metadata assessment.

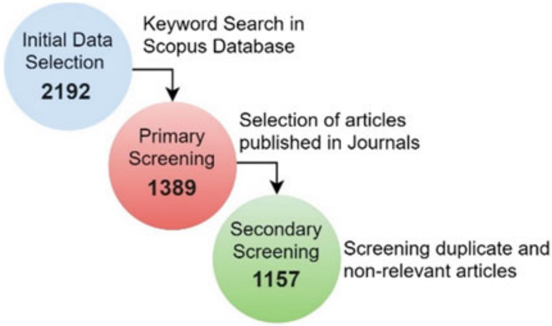

Fig. 3 Steps of article selection for bibliographic study

4.1 Selection of Research Articles

In the study, research papers were identified and selected following a three-step systematic process, as shown in Fig. 3. The first step determines initial data using the Scopus database for the last 10 years (2010–2020). In the initial search of research data, keywords like 'supply chain analytics,' big data analytics in the supply chain, business intelligence in the supply chain, 'analytics in supply and demand,' expert system in the supply chain, 'decision system in the supply chain,' 'quantitative techniques in the supply chain,' and other related keywords were used. The initial search was limited to the abstract, title, and keywords of the research articles. Through the initial search, 2192 articles were identified. In the second step, the primary screening of identified research articles was carried out. All the literature other than research papers published in journals were removed from the initially identified research articles in this screening. Through the primary screening, 1389 research papers on supply chain analytics were identified. In the last step of research article selection, secondary screening was carried out. All the duplicate entries and non-relevant articles were screened out from the selected research articles. A remaining of total of 1157 articles were selected for the bibliometric study.

4.2 Analysis and Discussion on the Bibliometric Study

The selected data for the bibliometric study of SC analytics is analyzed over yearly research trends, the research focus of various countries, different subject areas of SC implementations, most contributing journals and authors, and most influential published articles in the field of SC analytics.

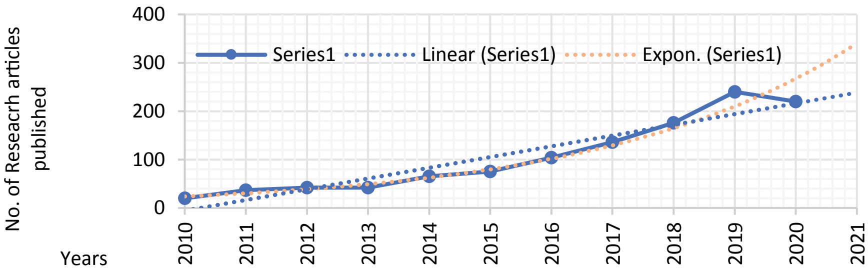

Fig. 4 Research trend for SC analytics

(I) Annual research trend for SC Analytics: The distribution of research articles published in journals in the last 10 years is provided in Fig. 4. The figure shows steady growth in articles published in journals in the previous decade with linear as well as exponential trend. From the year 2015, exponential growth can be observed in publications of articles in SC analytics. This exponential research trend proves the impact of analytics in SCM and the involvement of the researcher in exploring the analytics and data science areas to manage SC activities.

(II) The research focuses of countries in SC Analytics: Top 10 countries that have the most publication in SC analytics areas in the last 10 years is shown in Fig. 5. The USA, China, and India hold the top three ranks in the total number of published articles by countries with 327, 235, and 133 published articles, respectively. The top 10 list of countries in research publication in SC analytics holds a mix of developed and developing countries prove the seriousness of researchers towards SC analytics irrespective of geographical domain.

(III) Research in SC analytics in different subject areas: Although the implementation of SC analytics is evident in most subject areas, few disciplines dominate in the availability of research literature and scope of research work in SC analytics. The top 5 subject areas having the most published articles in SC analytics include business management, engineering, decision science, computer science, and social sciences, as shown in Fig. 6. As research can belong to more than one subject area,

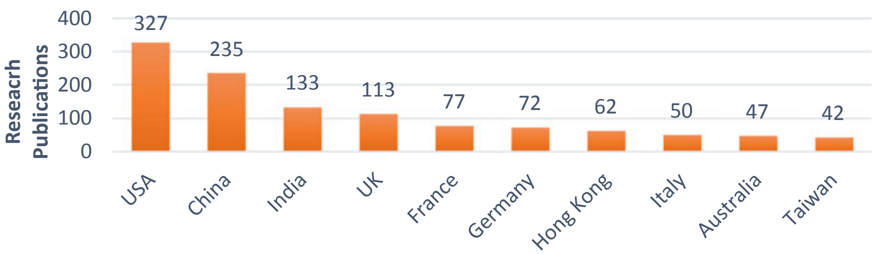

Fig. 5 Top 10 research publications by countries

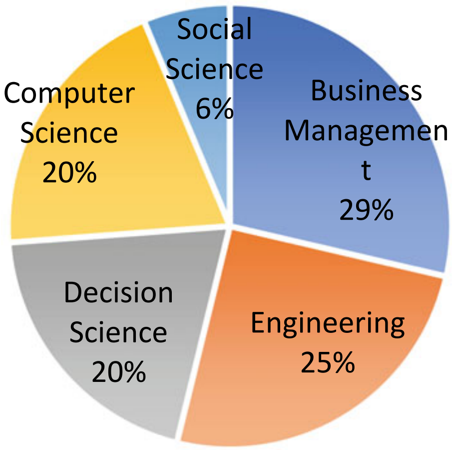

Fig. 6 Percentage contribution of SC analytics research in subject areas

there are adequate publications in these subject areas with 573 publications in business management, 505 publications in engineering, 400 publications in decision science, 397 publications in computer science, and 127 publications in social science disciplines in last 10 years.

(IV) Contributions by journals and authors: Figures 7 and 8 show the list of top 5 authors and journals with maximum publications in areas of SC analytics in the last 10 years. All the top contributing journals are premier in operations and supply chain management and are also listed in the influential Web of Science database. The high publication count in these reputed journals can be considered a good measure for the scope of SC analytics in future research publications. Among the most contributions of authors in the SC analytics area, Gunashekaran, A. has a maximum number of 25 research articles. A good number of publications in the same SC analytics areas by authors show the possibility of multiple explorations of the research area along with the scope of multiple publications.

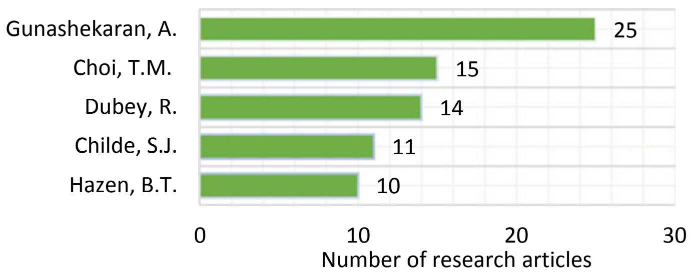

Fig. 7 Top 5 most contributing authors

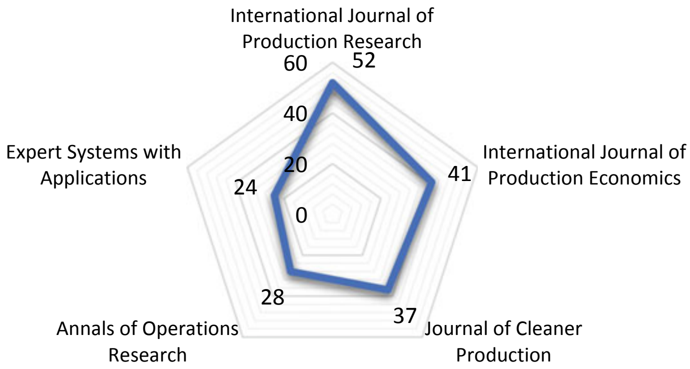

Fig. 8 Top 5 most contributing journals

(V) Research articles by count of citation: In all the identified research publications of SC analytics in academic journals in the last 10 years, Table 1 provides the top 5 articles with the highest citation counts. In the last 10 years, the highest citation received on an article is 527, published in 2013, followed by the second article with 434 citations published in the year 2017.

(VI) Insights and future directions: The study provided a brief understanding of SC analytics, highlighting the challenges and integrating the usability of analytics in the SCOR model to meet the challenges. Further, the bibliometric study provided an overview of research publications in the area of SC analytics, the outcome of which shows a notable trend of inclusion of analytics and business intelligence in different business supply chain operations. The research publication trends of the last decade show significant growth in the SC analytics research literature. While the area of SC analytics is still novel, the rapid transformation of the traditional supply chain to an integrated supply chain has forced academicians and researchers to explore the role of SC analytics in different processes of SCM, which resulted in significant research publications in past years. Insights of the bibliometric study also substantiated that reputed journals are giving space for SC analytics-based research work. With possibilities of good citations, the scope of publication in reputed academic journals, and the integration of supply chain analytics in most subject disciplines, SC analytics has an enriched prospect in future explorations and studies. Under the future prospects, this research study can provide a basis for an extensive literature review for the SC analytics domain. The research study is limited to the research database of Scopus, and future work can include other reputed databases like Web of Science for a holistic review of SC analytics literature.

Table 1 Top 5 research articles by citation count

SN	Authors	Title	Year	Journal	Citation
1	Waller M.A. and Fawcett S.E	Data science, predictive analytics, and big data: A revolution that will transform supply chain design and management	2013	Journal of Business Logistics	527
2	Wolfert S. et al.	Big Data in Smart Farming—A review	2017	Agricultural Systems	434
3	Wang G. et al.	Big data analytics in logistics and supply chain management: Certain investigations for research and applications	2016	International Journal of Production Economics	401
4	Hazen B.T. et al.	Data quality for data science, predictive analytics, and big data in supply chain management: An introduction to the problem and suggestions for research and applications	2014	International Journal of Production Economics	351
5	Gunasekaran, A. et al.	Big data and predictive analytics for supply chain and organizational performance	2017	Journal of Business Research	238

5 Conclusion

This paper attempts to provide a brief review of SC analytics and provide a bibliometric study of past research for the last 10 years. The paper provided a supply chain framework of challenges associated with supply chain processes. The paper also discussed the role of SC analytics and mapped the different roles with the SCOR model. The paper provided another framework of SC analytics related to plan, source, make, deliver, and return phases of the SCOR model along with interrelation with different supply chain processes. The bibliometric study provided in the paper discusses the paradigms of trends, demography, research disciplines, and influential journals and publications associated with the literature of SC analytics. The paper is a short assessment of research literature on SC analytics, which is limited to data collection constraints. The study can be used in future work for a more comprehensive review of research literature on supply chain analytics.

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Shaping a New Shopping Experience for the Post COVID-Era

Ankit Pal and Saptarshi Kolay

1 Introduction

The outbreak of the coronavirus has changed how people behave both inside and outside their homes. Before the virus outbreak, in many cities worldwide, consumers depended on supermarkets for purchasing items. Most of these big supermarkets depend on long supply chains and primarily focus on increasing their stakeholders' profits instead of supporting local demands and livelihoods [1]. Local stores (such as the ones dealing in groceries and household supplies) suffered as supermarkets were rising. However, Covid-19 travel restrictions have put a strain on supermarkets. This has made us realize that local stores (which depend on shorter demand–supply chains) are the need of time [2].

After and during the pandemic, it was observed that local stores are necessary for a neighbourhood's survival. Many of such stores have now tried to adapt to home-delivery logistics too. This research explores a perspective on supporting local stores and markets, which can be essential in economic and social recovery from the coronavirus.

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2 Research Motivation

After observing shifts in consumer behaviour and retail operation, we felt the requirement for more design-driven research in the microeconomy of the Indian *Kirana* stores. We noticed some store retailers taking orders on call and keeping them ready for pickup by customers. Some of these retailers also provided Home-Delivery options, sensing their customers' reluctance to stay out of the home. Considering these shifts, we were interested in whether digital media could help create a new paradigm in retail.

2.1 Review of Literature

According to recent world Covid-19 reports, a sharp decline in mobility has been observed across many sectors, from retail to recreation, leisure travel, and even work [3]. The ongoing crisis has altered what, how, and where we shop. The risk of infection has made the eventual fate of the in-store shopping experience quite vulnerable. In the United States, accessibility of e-commerce platforms and cleanliness concerns have led shoppers to switch stores, with many shoppers moving away from their primary shop. Numerous shoppers have attempted new methods of purchasing: purchase online from e-commerce platforms, pick up in-store, and curbside pickup [4].

Moreover, consumer spending has shifted from discretionary categories, such as apparel and vehicles, to essentials such as groceries and household supplies [5].

This crisis has prompted a shift in people's perceptions and behaviour, affecting urban freight transport demand and changing demand for contactless services provided by e-commerce platforms [6].

As the world also sees advancements in Industry 4.0, switching to digital platforms might prove vital for pandemic recovery. There is a need to transition to more minor labour-intensive operations [7].

2.2 Research Gap

The coronavirus pandemic has piqued interest for research in many fields. However, since the crisis is relatively recent, not much literature is available on the internet regarding the small Indian retail industry. Extensive research has not been conducted on the shifts in behaviour of Indian consumers after the pandemic. A large fraction of Indian retailers dealing in consumer staples still operates in brick and mortar [8]. In the recent crisis, we observed how small *Kirana* (retail) stores were impacted due to prolonged lockdowns and an increased tendency in consumers to shop on large e-commerce platforms [5].

Given the loss of employment and income cuts, spending within limits is critical for sustenance. However, the twenty-first century consumer needs to acknowledge how these small local stores had been long part of the Indian *Middle-Class consumer* lifestyle. Companies like Grofers and Bigbasket have now become big players in the domain of grocery shopping. But, due to their business model and their own brand labels, there is a lack of visibility into the stores' inventory levels from where they pick up products. This might impact customer experience. These retail giants favour only those stores with whom they tie-up with. This makes us think about how other small retailers operate and how do consumers purchase during COVID restrictions.

2.3 Research Questions

We observed some shifts in consumer behaviour and how small retailers operated during April and May 2021, when COVID cases peaked in some Indian states. Due to the risk of infection, users wanted to abstain from going outside and avoid long queues at shops. Some of them even resorted to home delivery. We noticed a small fraction of retailers in Delhi and Roorkee, who used to take orders on call and keep them ready for customers to pay and pick up their items. Through this research, we wanted to understand the answers to a few questions:

1. Has Covid-19 also created a new segment of consumers with different behavioural patterns?
2. Can user experience Design-Based research help bridge the gap between the small retailer and the consumer?
3. What can be the benefits of digital intervention in the retail sector through user interface development?

3 Methodology

This research follows an inductive model of approach. The result of the research is formed after several iterations of design development and feedback from users (Fig. 1).

3.1 Problem Identification

We adopted the double diamond process for identifying the issues and proposing a solution for the same [9] (Fig. 2).

Using the double diamond model, multiple problems (caused due to the pandemic) were discovered and placed in an 'affinity diagram.' The next step was to cluster

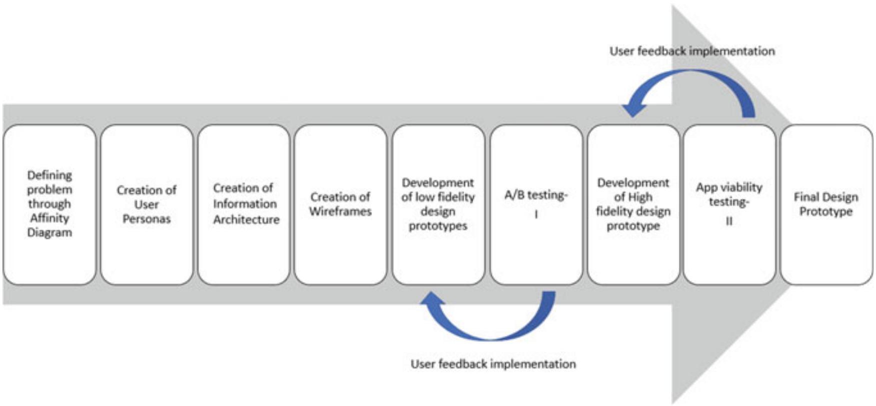


Fig. 1 Flow of research methodology; A co-design based research

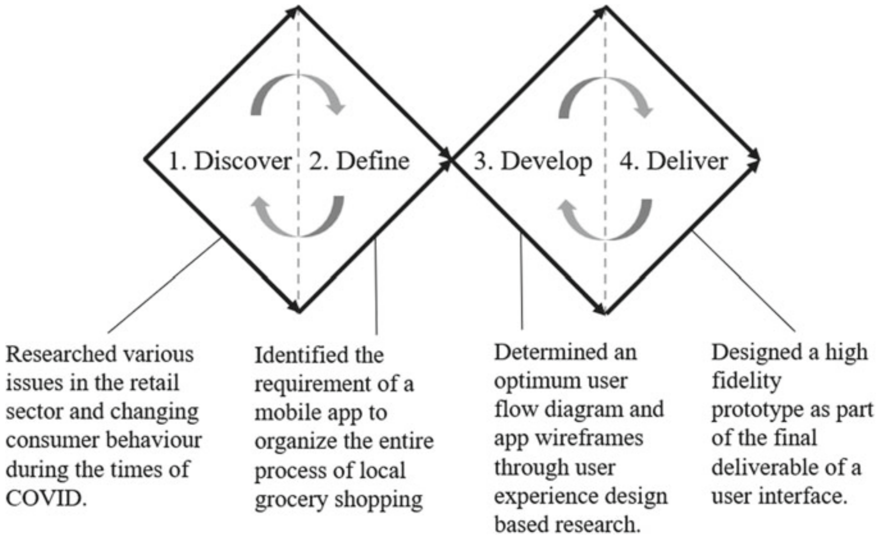


Fig. 2 The double diamond process used for the research

different such problems into subgroups in order to define a target subgroup. We identified issues in the local retail sector, mobility, and shifts in consumer behaviour.

Subsequently, an online questionnaire survey was conducted to understand these behavioural shifts and the type of solution developed for pandemic recovery. After the survey, we decided to develop an App-Based solution related to online grocery shopping from local stores since there is also a growing demand for e-commerce applications.

As a part of the user research, user personas were created to understand different types of users. This also gave insight into how the users might respond to certain application features to be developed.

Next, we conducted an online card sorting activity to visualize the user flow on the app.

Users were provided with a set of cards, which mentioned several generally observed actions while shopping on online platforms. A few of the actions mentioned were searching the product in the search bar, comparing prices, checking for home delivery. The users performed two tasks. First, to select the actions which they usually perform while shopping online. Second, to make a sequence of actions to purchase grocery items from the app wireframe, from start to end.

Based on the card sorting activity, information architectures were created for further design development. Next, we created wireframes that were presented to the users.

3.2 Wireframing Process

A 'Wireframe' is a skeletal outline of an application or a webpage. Wireframes visualize the structure, page layouts, user flow as well as user interaction. Depending on the level of detail required, wireframes can be sketched on paper or created digitally [10].

Since the research is based on a mobile app, a frame size of (412*847 px) was selected (these dimensions may vary slightly across other models).

We conducted two user testing. For User Testing-I, two different app wireframes were created based on different information architectures.

The first wireframe primarily focussed on the shop experience and checking nearby shop locations through the GPS. The user could set a shopping radius, select a shop, and purchase items. Once the bill is made, users could schedule a time for an in-store pickup.

The second wireframe deferred slightly in the user flow. It was based on a digitalized version of shopping methods in the offline/'in-person' mode. The wireframe allowed the users to make a shopping list in the app, and the app would automatically find the listed items in nearby shops. Users could choose home delivery or set an in-store pickup time to pick their order from a shop.

The two wireframes were created on an online whiteboard platform named Miro.

We then proceeded with our first app viability testing (A/B testing).

3.3 User Testing (I and II)

Snapshots of each wireframe were put slide-wise in Microsoft PowerPoint. From each button in a single frame, a hyperlink was formed to another corresponding frame. Since there were two wireframes, we prepared two different PowerPoint presentations. Using Google Meet, we presented the two wireframes to users, where they were expected to navigate through the app for purchasing a grocery item by clicking on buttons visible on the screen.

After analyzing the observations from the first user testing, a new User-Optimized wireframe was created. The user flow was improved according to the response from the users. Now users could follow any one of the three user flows included in the new wireframe; First, users could directly search for the item in the search bar and simultaneously add it to the cart. Second, they could set a shopping radius, select a shop and add items for billing. Third, they could make a shopping list, and after the app would find the listed items from nearby shops, they could add them to the cart or search for more products. After the cart is prepared, users could choose for an in-store pickup or home delivery. The home screen was also improved. It included a carousel of nearby shops, and their distance from users' location could be adjusted according to convenience. Few crucial sections, as observed in online shopping platforms such as Amazon, Gofers, and Flipkart, were added. Some of the sections added were product categories, discount house, and Covid essentials.

The User testing -II had a similar methodology of conduction. In this case, the testing was conducted on Google Meet with the snapshots of the single new wireframe. The task was to buy flour and cooking oil using the optimized app wireframe.

4 User

The primary user group identified through the research was the working adults, homemakers, and students from colleges who do not want to spend much time inside crowded shops due to the risk of infection. Other problems include users not being able to afford high delivery prices. Few users also preferred to purchase items based on their loyalty to local stores, which earlier was not visible to them in few other grocery apps.

A total of 16 user responses were collected. The users mainly varied from students to homemakers and office workers. Most of the users were from the age group of 15–30 years, majorly belonging to the Delhi-NCR region. Few other users belonged to the states of West Bengal, Uttarakhand, Rajasthan, and Telangana.

5 Observations and Analysis

The following sections describe some important observations and analysis made from the card sorting activity and app usability testing. Most of the users indicated towards similar user flows. However, there were also users who depicted different user preferences.

5.1 Card Sorting Activity

Out of 15 users whose responses were collected, 12 were from the 15–30-year age group and the rest from 30–45. As a common observation, most people tended to use the search bar to find and add items quickly. Most of them preferred to choose the home delivery option, while the rest chose to pick up the order themselves. Another interesting observation was that some users chose to purchase items after seeing the shop profile due to shop loyalty.

5.2 Low Fidelity Design User Testing-1

Fifteen users were shown two versions of the app wireframe (low fidelity prototype) and given a task of purchasing 2–3 items through the app. The users were supposed to navigate through the available icons and pages to accomplish the result.

5.3 Some Observations from User Testing-1

Most of the users did not follow the expected route of both the Wireframes. Only 3/15 users having a tendency of shop loyalty could smoothly navigate through the first wireframe. Some of the users felt confused while seeing the GPS map on the home screen of the first wireframe. Most of the users preferred to use the search bar more during online shopping, but the 2nd wireframe was not found to be optimized for that action. Only 2/15 users chose to prepare a shopping list using the second wireframe but found the process of finding available items and repeating it quite tedious. Some of the users had predetermined brands of items that they wanted to buy and wanted to use the search bar directly. Also, most of them mentioned that they would prefer home delivery at affordable prices, rather than going to pick their order themselves (due to increased risk of infection).

5.4 The Need for User Testing-II with an Optimized Wireframe

The wireframes were created assuming that users would follow the new pattern of the app. As it was observed from the previous testing, users did not follow those flow patterns. They preferred to navigate through the search bar, which meant that searching and search results had to be optimized for the least time wastage. This, in fact, indicated a need for a second round of user testing with an optimized wireframe.

5.5 Observations from the Second User Testing-II

Most users could easily navigate through the app by using the search bar and simultaneous add to cart option. 3/16 users preferred to select a shop of their choice and buy items from there. The average time of purchasing through this app was observed to be ~169 s, with the minimum being 117 s and the maximum being 298 s. Also, Users from the age group of 15–30 years took less time to navigate than those in the age group of 30–45 yrs. The table below presents some more observations from the final round of testing (Figs. 3 and 4 and Table 1).

With feedback from the users after the second user test, the final High-Fidelity design prototype was developed. A few frames are shown above.

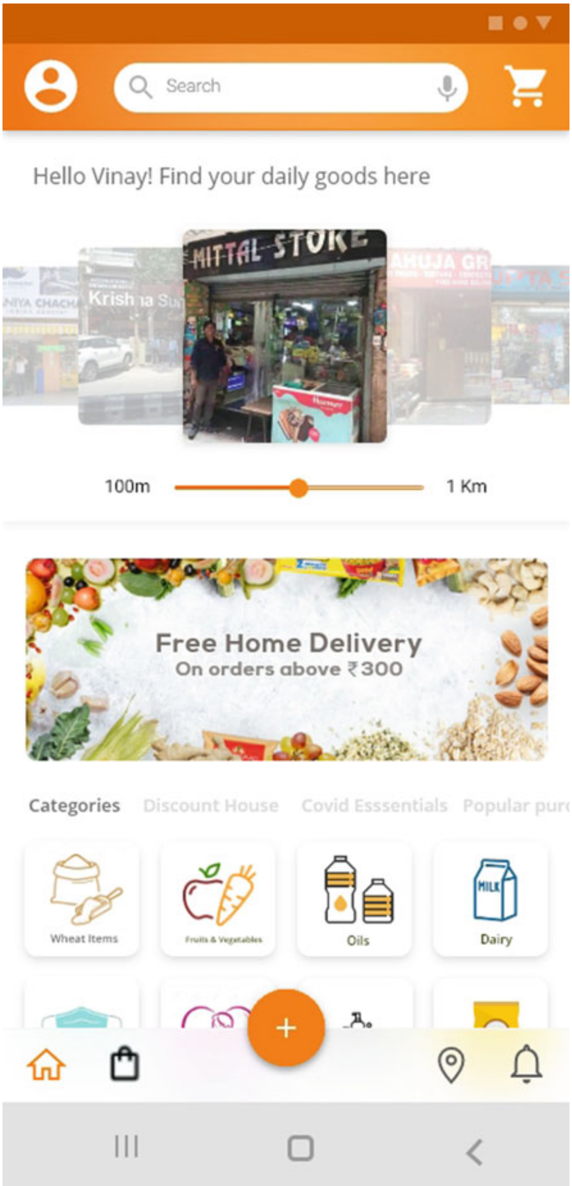
6 Conclusion

Local grocery stores have long been part of our economies. With the risk of infection still looming, there is a need for a swift transition of small local stores to digital avenues. During COVID restrictions, a short trip to these stores or home delivery can support these stores, which are also affected due to falling customer spending. This research presents an opportunity to rewire the COVID generation to a sustainable way of living, keeping economies of consumption, health, and saving in mind. We have observed how this pandemic has sparked a revival in local shopping trends Through our research, we have found that there is a large segment of consumers who would like to switch to the option of home delivery, so that they could avoid long queues at local shops. Also, there is a small segment of consumers who would like to walk down or cycle to the shop for picking up their order, given the entire shopping and billing experience is online. This indicates that the next normal in the retail sector is going to be the 'Digital Experience of Shopping'.

Through this research, we also observed that the user experience design of the app developed with each iteration of user testing, feedback, and implementation. It made the solution feasible and a project that has been co-created, verified, and tested by the users.

The current app prototype lets consumers abstain from physical proximity and reduce the risk of the virus spreading. Setting Self-Pickup times, online payment, easy switchability options, and the ability to see and buy items from the stores they prefer online make the customer experience Hassle-Free and satisfying. From the small retailers' end, online stock management, bill and order status tracking, and online transactions, inbuilt shop profile builder would help the business grow. Keeping orders ready beforehand would help save time. However, designing the prototype for the retailers requires further research and investigation, and we encourage more people to ponder upon how it could be developed for a digital platform. This prototype presents us with an opportunity to support and boost the microeconomy of the

Fig. 3 More frames developed for the application prototype



small Kirana stores. Supporting local shops and markets can lead to socio-economic recovery and urban resilience from shocks (such as the pandemic).

In the coming years, we expect e-commerce platforms to see tremendous growth due to the absence of physical presence while purchasing. This crisis has urged everyone to advance towards a digital experience of the physical world. In the context

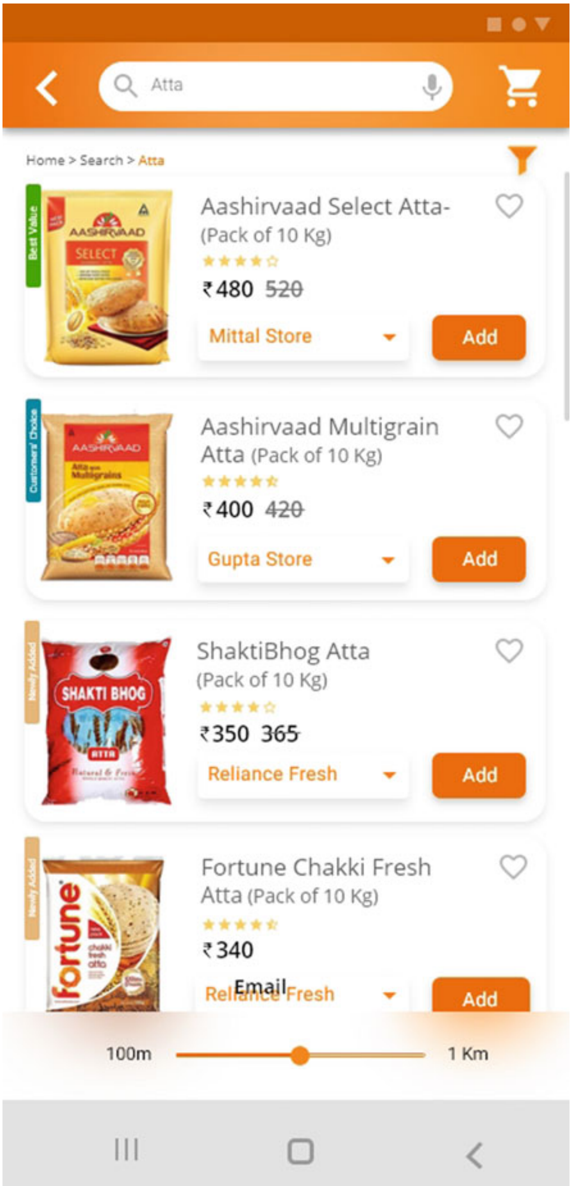


Fig. 4 Frames developed for the application prototype

of a holistic recovery from the pandemic, this App-Based solution might prove essential in the revival of the local economy. If implemented systematically backed by local grocery store operators, this solution can be scaled up across many cities and become an entrepreneurial product, benefiting millions affected by the pandemic.

Table 1 Few observations from final user testing

User no	Age group (yrs)	Time of completion (s)	User flow	Instore pickup/home delivery
User A	15–30	150	Search and add to Cart	Home delivery
User B	15–30	126	Search and add to Cart	Instore pickup
User C	15–30	160	Search and add to Cart	Home delivery
User D	15–30	208	Search and add to Cart	Home delivery
User E	15–30	193	Go to shop, prod. categories, Add to Cart	Home delivery
User F	15–30	117	Search and add to Cart	Home delivery
User G	15–30	119	Search and add to Cart	Home delivery
User H	15–30	119	Search and add to Cart	Home delivery
User I	15–30	208	Search and add to Cart	Instore pickup
User J	15–30	210	Shop by category, Add to Cart	Home delivery
User K	30–45	182	Search and add to Cart	Instore pickup
User L	15–30	150	Search and add to Cart	Instore pickup
User M	15–30	162	Search and add to Cart	Home delivery
User N	30–45	298	Go to shop, prod. categories, Add to Cart	Instore pickup
User O	45–60	171	Search and add to Cart	Home delivery
User P	15–30	130	Go to shop, prod. categories, Add to Cart	Instore pickup

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Simulation-Based POLCA Integrated QRM Approach for Smart Manufacturing

Sandeep Kumar, Sanyapong Petchrompo, Tanveer Ahmed, and Amit Kumar Jain

1 Introduction

The fourth industrial revolution (also known as Industry 4.0 or smart manufacturing) is one of the critical research areas in advanced manufacturing. Smart manufacturing has its roots in artificial intelligence, machine-to-machine communication, and sensing technology. Although these technologies make machines intelligent, such intelligence in manufacturing planning eludes literature. Moreover, digitalisation and Industry 4.0 have enabled real-time interaction of customers and suppliers with manufacturing systems. Therefore, it is expected that significant demand variations, an increase in the number of variants, and additional demand for customised products will be more common in the case of next-generation intelligent factories. In addition, fast and on-time delivery, reduction in lead time, production cost saving, profit maximisation, etc. are conventional requirements of any manufacturing organisation. The conversional requirements and new requirements due to digitisation making decision-making tasks more complex. Production scheduling, inventory control, material control, maintenance planning, and raw material planning become

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more challenging in such situations. This necessitates a high level of responsiveness in the value chain to sustain a competitive economy. Therefore, quick response to dynamic situations created by machine failures, wide variety, change in demand, volatile market conditions, uncertainty in supply, etc. is essential in captivating the advantages of digitisation in industries. Consequently, an innovative quick response system is needed to handle the challenges and opportunities offered by smart factories under Industry 4.0.

Quick Response Manufacturing (QRM) can be crucial in a complex production system because it provides faster product deliveries [1]. QRM is a company-wide strategy that pursues increasing the throughput by reducing the lead times across all operations, covering all aspects of manufacturing, design, planning and control, and supply management. On the other hand, production scheduling, inventory control, and material control can be handled by Paired-cell Overlapping Loops of Cards with Authorization (POLCA). POLCA is gaining significant attention in industrial production control systems for high-mix, low-volume, and custom-made products. A POLCA integrated QRM approach is developed and tested in the presented research to explore its potential benefits.

Several companies have implemented QRM strategies and achieved excellent results [2, 3]. The crucial outcomes were a reduction in lead times (80–95%), reduction in product cost (15–50%), improved delivery performance (from 40 to 98%), and more than 80% waste reduction. QRM supports the use of POLCA card systems, which is a hybrid push–pull strategy used between cells to reduce lead times. The main strength of POLCA is that it can be integrated with existing Material Requirement Planning (MRP) and Enterprise Resource Planning (ERP) systems [4, 5]. POLCA is well suited for customised parts as the jobs are transferred differently from one machining cell to another. Thus, POLCA was considered one of the integral components of the overall QRM strategy for a company-wide approach. Suri [1] explained that scheduling should be done on capacity rather than materials at a specific workstation. Subsequently, several researchers investigated the benefits of the POLCA system. Pieffers and Riezebos [6] provided a critical description of the main features of POLCA and provided details on the design and performance analysis of a system operating under POLCA control. Some researchers compared the efficiency of POLCA with other material control systems, such as the workload balancing capability of CONWIP, POLCA, and multiple CONWIP (m-CONWIP) and found that POLCA provides better results [7].

From the above discussion, it is evident that the integration of QRM and POLCA can be beneficial. However, to the best of our knowledge, such integration does not exist in the current literature. Therefore, the present paper proposes a POLCA integrated QRM approach for the job shop environment. Though imperative, integration of multiple operation functions brings in computational complexity. Studies have shown that even solving the static single machine scheduling problem without considering maintenance is NP-hard [8]. And the integration of multiple functions exponentially increases the computational complexity. Simulation-based techniques are widely used to solve such complex problems [9–11]. Therefore, simulation-based techniques are used to solve the present problem. The approach is demonstrated through a complex manufacturing scenario. Further, the performance of the approach under dynamic conditions is analysed. Lastly, such a novel manufacturing planning approach will have its roots in the technology enablers of next-generation manufacturing systems.

The paper is organised as follows. Section 2 presents the problem description. The simulation-based POLCA integrated QRM approach is discussed in Sect. 3. Section 4 presents results and performance analysis under dynamic conditions. Lastly, Sect. 5 concludes the paper and identifies the future scope of work.

2 Problem Description

The observations and findings from the above literature review are studied in a precision parts manufacturing company. The manufacturing scenario is of a job shop kind of environment. Customers can place an order using a mobile App or web-based application. The manufacturing system is consisting of eight different machines (M1, M2…., M8). The system produces ten other products (jobs) (J1, J2, …, J10). The machines are used to process ten different jobs with a pre-specified flow in the system, as shown in Table 1.

The jobs arrive randomly. The pattern of inter-arrival time of jobs follows an exponential distribution with parameters as mean arrival rate from past data. The pattern of service time of each machine is also following an exponential distribution. The mean arrival rate and mean service rate are shown in Tables 1 and 2, respectively. These are obtained from past data. The due time for jobs is decided by the customer and is shown in Table 1. The ORACLE database is used in the manufacturing system for data collection and management. The aim is to find out the dynamic sequence (release authorisation) of jobs at each machine to meet the due date and at the same time control the material flow (reducing WIP) in each stage of the system to improve delivery performance. In this problem, the planning horizon is considered as one week, i.e., 168 h.

3 Simulation-Based POLCA Integrated QRM Approach for Intelligent Manufacturing

This section puts forward a pioneering simulation-based POLCA Integrated QRM Approach for next-generation intelligent manufacturing. The methodology for solving the above problem is shown in Fig. 1. It contains an information unit, the approach, and performance analysis.

Table 1 Properties of jobs

Route	Jobs	Process flow				Arrival rate (Jobs/Week)	Flow time (Hours) $\sum WS_i$	Due date per job in hours
1	J1	M1	M3	M4	M7	500	2.49	3.11
2	J2	M2	M5	M4	M8	300	2.57	3.21
3	J3	M5	M4	M7	M6	200	3.11	4.04
4	J4	M1	M3	M6	–	450	1.97	2.64
5	J5	M1	M4	M7	M8	300	2.48	3.00
6	J6	M1	M2	M5	M8	400	2.39	2.97
7	J7	M2	M3	M6	–	250	1.97	2.62
8	J8	M2	M4	M7	–	200	1.95	2.44
9	J9	M2	M5	M8	–	500	1.81	2.26
10	J10	M1	M3	M7	M8	350	2.26	2.70

Table 2 Properties of machines

Machines	Utilisation factor	Arriving total jobs at machine per week	Service rate (Jobs/Week)	Mean cycle time (Hours)
M1	0.85	2000	2352	0.07
M2	0.82	1650	2012	0.08
M3	0.80	1550	1937	0.09
M4	0.85	1500	1764	0.1
M5	0.85	1400	1647	0.1
M6	0.82	900	1097	0.15
M7	0.83	1550	1867	0.09
M8	0.80	1850	2312	0.07

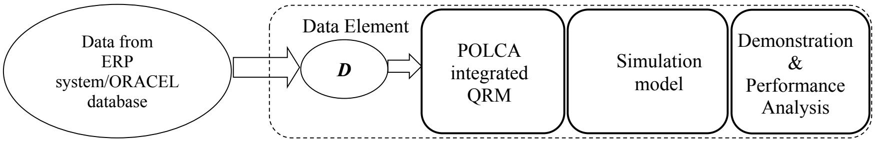

Fig. 1 The methodology of the research work

3.1 Data Element

The central ORACLE database used in the manufacturing system for its data collection and management provides the required inputs to the system through its data element. The inputs are of two kinds, viz., static and dynamic. Static inputs include details about the system, i.e., number of machines, number of jobs to be processed, process flow, parameters like job's cycle time, and utilisation factor. The dynamic inputs include product demand, arrival rate, unexpected events like machine failure, etc.

3.2 POLCA Integrated QRM Approach

The development steps of the approach are as follows.

3.2.1 Define strategic goal

In QRM, an essential part is to define the strategic goal. After studying the manufacturing system and discussing it with the company personnel, we have identified its intent to improve delivery performance. It is defined as follows:

$$\text{Delivery performance (\%)} = \left(\begin{array}{l}\text{On} - \text{time delivered items} \; / \\ \text{Total delivered items}\end{array}\right) 100 \tag{1}$$

3.2.2 Computing lead time and release authorisations

POLCA is generally suitable for a job shop environment with a wide variety and highly dynamic market conditions. The basic concept of POLCA is to use cards to show the free capacity between two cells. The release of jobs may be done using the conventional MRP system. MRP system uses each cell's planned due times to determine when each cell in product routing may begin processing that job. This is called authorised time. However, the actual release will start only after receiving the required POLCA card. A job waiting in the input buffer for a cell cannot be started until the right POLCA card is available and its authorised time has passed. In multiple jobs, a job with the earliest authorisation time will qualify first to search for the required POLCA card.

The release authorisation times are computed for each job at each machine of the route. First, calculate the Due Date (DD) of the route. It is 'a (>1)' times of the flow time of the route.

$$\text{Due date of } kth \text{ route} = a \times \sum WS_k \tag{2}$$

Next, calculate Due Time (DT) at each machine of routes to implement the POLCA authorisation rule. On or after this due time, a job will be released, and in the case of multiple jobs, a job with the highest slack (difference between current flow time and due time) will be released first. Current flow time is the time spent by a job in the system at the time of computation of release authorisation at a machine.

One of the features of QRM is to reduce lead time. Here, QRM is integrated with POLCA, which in turn leads to a reduction in lead time.

The due time calculation and how to sequence multiple jobs at a machine has been illustrated through an example shown in Fig. 2. Consider a system where job J1 is processing through 3 machines. The flow time of the route is 4.5 h, and the due date is 6 h (1.33 times of flow time). PT is the machine's processing time, and WS

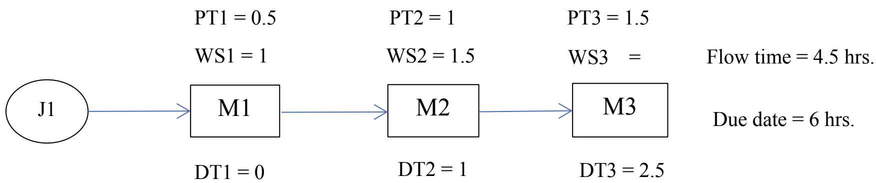

Fig. 2 Due time calculation

is the estimated average lead time (waiting time is system). Here, WS is considered as base. So, machines 1, 2, and 3 will release on or after 0, 1, and 2.5 h.

Now consider a machine processing three jobs (p, q, and r). Their due times are 1, 2, and 3 h, respectively. The current flow times at the machine of these jobs are 1.3, 2.0, and 3.2 h, respectively. Thus, the slack is maximum for job 'p' and minimum for job 'q'. So, sequence to be is p-r-q.

After deciding the processing sequence, the machine ensures the availability of POLCA. If cards are available for each job, then go with the sequence; otherwise, process the next job whose POLCA card is available as per the sequence.

3.2.3 Computing the number of POLCA cards in each loop

POLCA cards are assigned to specific pairs of cells, chosen as follows. Within the planning horizon, if the routing for any order goes from any cell (say A) to another cell (say B), the pair of cells A and B is assigned several POLCA cards, all of which are called A/B cards. The POLCA cards for each pair of cells stay with a job during its journey through both cells in the pair before they look back to the first cell in the pair. For example, an A/B card above would be attached to a job as the job entered cell A. It would stay with this job through cell A and as it goes to cell B, continue to stay with the job until cell B has completed it, and while the job moves on to its next cell (say C), this A/B card would be returned to cell A. After the job arrives at cell B, since it is destined for cell C, cell B needs to have a free B/C POLCA card before starting the job on the product. Thus, jobs in cell B will carry two POLCA cards with them as part of two card loops. The overlapping loops in POLCA act as a buffer to absorb variation in demand and product mix. This allows each cell to balance its capacity as best as it can for the current mix. The concept of POLCA material control is shown in Fig. 3.

The number of POLCA cards for each loop is shown in Table 3 and are computed using the formula:

$$\text{Number of POLCA Cards between x/y loop} = \left(WS_{Mx} + WS_{My}\right) * \left(N_{x,y}\right)/T$$

where WS_{Mx} and WS_{My} are estimated average lead time (waiting time is system) for machines M_x and M_y in a POLCA loop. $N_{x,y}$ is the total number of jobs from machine M_x to M_y during the planning period T.

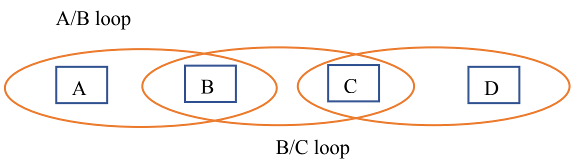

Fig. 3 Concept of POLCA material control

Table 3 POLCA cards for loops

Loops	Sum of lead times (Hours)	Total jobs processed through a loop	No. of POLCA cards
M1-M3	0.910	1300	8
M2-M5	1.144	1200	9
M5-M4	1.315	500	4
M1-M4	1.111	300	2
M1-M2	0.940	400	3
M2-M3	0.897	250	2
M2-M4	1.099	200	2
M3-M4	1.068	500	4
M4-M7	1.164	1200	9
M3-M6	1.284	700	6
M5-M8	1.043	900	6
M3-M7	0.963	350	3
M4-M8	0.998	300	2
M7-M6	1.380	200	2
M7-M8	0.892	650	4

3.3 Simulation Model

Generally, real-world manufacturing operations involve many machines, jobs, and complex flow of materials. The performance evaluation for such a complex system is computationally challenging. A simulation model is commonly used in such situations. Moreover, the presence of stochastic variables like time to repair, number of failures, etc. makes the simulation model necessary. The job sequencing problems are well-known and proved NP-hard problems [12, 13]. Present work considers the joint problem of job sequencing and inventory control for a complex multi-machine system with stochastic parameters, which significantly increase the problem complexity. Researchers generally use the simulation-based method to solve such problems [14–16]. Thus, a simulation-based method approach is used in this research to solve the problem. Jobs characteristics, machines properties, process flow, etc. are coded in Witness 14 simulation platform [17].

The simulation model automatically communicates with the central database (ORACLE) of the system. This enables capturing any parametric changes like demand variation, job arrival pattern changes, capacity changes, etc. Moreover, the model can utilise Cyber-Physical System (CPS) and Industrial Internet of Things (IIoT) capabilities.

4 Results Using Simulation-Based POLCA Integrated QRM Approach

First, the results for the presented industrial case (Sect. 3) are obtained using the proposed approach. Additionally, the performance of the approach under dynamic conditions is investigated. The considered planning horizon is 168 h, and the number of simulations performed per scenario is 1000. The simulation model is shown in Fig. 4a, b. Figure 4b shows a detailed view of the model. The POLCA and properties of machine M1 are shown in Fig. 4b. The model is linked with the central database

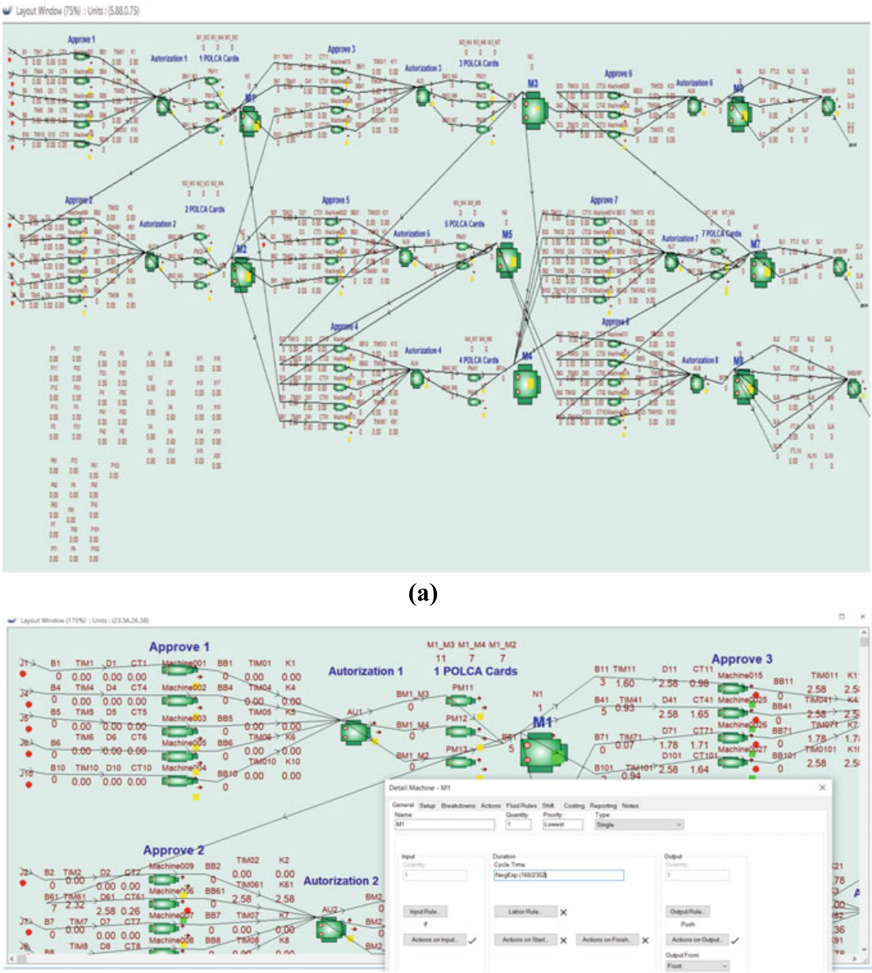

Fig. 4 **a** Simulation model. **b** A part of Simulation model

of the system to fetch all input parameters. Also, machine health data from sensors goes to a central database and is reflected in the model. The model is connected to various department databases and communicated whenever required. The identified QRM Goal is to improve delivery performance. The simulation model provides the dynamic job sequence (release authorisation) of jobs at each machine to meet the due date and at the same time control the material flow (reducing WIP) in each stage of the system to improve delivery performance. The simulation results, i.e., machines utilisation, idleness and throughput per hour, average WIP, and delivery performance, are shown in Tables 4 and 5.

Table 4 Machine utilization and performance of the system

Machine	Actual utilisation (%)	Idleness (%)	Throughput (Jobs/hour)
M1	85.82	14.18	13.22
M2	81.19	18.81	10.79
M3	80.13	19.87	10.25
M4	84.62	15.38	9.83
M5	84.3	15.7	9.19
M6	81.88	18.12	5.93
M7	83.2	16.8	10.17
M8	79.77	20.23	12.12

Table 5 WIP and delivery performance of the system

Job	No. entered	Shipped	Avg. WIP in system	Flow time/job (Hours)	Due date (Hours)	Delivery performance (%)
J1	500,861	500,860	4.74	2.49	3.11	80.64
J2	298,966	298,966	3.48	2.57	3.21	82.23
J3	199,875	199,873	6.2	3.11	4.04	82.39
J4	448,830	448,826	3.72	1.97	2.64	81.88
J5	300,523	300,522	4.69	2.48	3.00	79.45
J6	401,446	401,444	4.31	2.39	2.97	82.81
J7	249,991	249,989	3.88	1.97	2.62	79.21
J8	199,562	199,562	2.58	1.95	2.44	77.78
J9	500,016	500,014	1.87	1.81	2.26	80.84
J10	349,540	349,539	3.15	2.26	2.70	77.58
The delivery performance of the system						80.64

Table 6 Effect of sequencing rule on the delivery performance of the system

Jobs	Arrival/week	FCFS	Seq
J1	500	80.64	80.64
J2	300	82.23	82.23
J3	200	82.39	82.39
J4	450	81.88	81.88
J5	300	79.45	79.45
J6	400	82.81	82.81
J7	250	79.21	79.21
J8	200	77.78	77.78
J9	500	80.84	80.84
J10	350	77.58	77.58
The delivery performance of the system		80.64	80.64

4.1 Performance Analysis Under Dynamic Conditions

The performance of the proposed approach is further analysed in dynamic conditions, i.e., change in job sequencing rule, change in system capacity, and due to date variation, for the case of Sect. 3.

4.1.1 Effect of Sequencing Rule on Delivery Performance

Industries may have different cost and delivery time agreements with other customers for products. So, in case of demand variation and an increased number of variants, the industry needs to prioritise manufacturing (sequencing rules) for the jobs. The company uses two sequencing rules: First Cum First Serve (FCFS) and job having highest slack processed first (Seq.). Each rule is considered at each machine. Therefore, Simulations are performed for these two cases. From Table 6, it can be concluded that sequencing rules have not significantly affected the system's delivery performance.

4.1.2 Effect of System Capacity on Delivery Performance

The capacity variation of the system affects its performance. And most industries face capacity variation frequently. Therefore, in case of capacity changes, the company should have a standard operating procedure to deal with the change. Thus, the effect of system capacity on delivery performance is analysed by varying numbers of POLCA cards. Total three cases are formed. The rising number of POLCA cards creates two instances of increased capacity by 2 and 5. And one reduced capacity case is generated by decreasing the number of POLCA cards by 1. From Table 7, it can be concluded

Table 7 Effect of number of POLCA Cards on delivery performance (%)

Jobs	Arrival/week	POLCA cards			
		Sufficient	Increase (+2)	Increase (+5)	Decrease (−1)
J1	500	80.64	80.49	80.49	81.12
J2	300	82.23	82.63	82.70	81.47
J3	200	82.39	82.59	82.59	81.84
J4	450	81.88	81.72	81.72	82.36
J5	300	79.45	79.59	79.55	79.61
J6	400	82.81	82.93	82.93	83.08
J7	250	79.21	79.29	79.29	78.51
J8	200	77.78	77.99	77.99	76.92
J9	500	80.84	80.67	80.63	81.19
J10	350	77.58	77.66	77.64	76.27
The delivery performance of the system		**80.64**	**80.68**	**80.68**	**80.23**

that variation of POLCA cards, i.e., system capacity, has not significantly affected the delivery performance of the system.

4.1.3 Effect of Different Due Dates on Delivery Performance

As, Industry 4.0 advocates the real-time interface of customers and suppliers with the manufacturing facility, the chances of changes in due dates are more frequent. Therefore, it is important to investigate the effect of different due dates on system performance for production sequencing and material control. For the investigation, the system is simulated for various multiplication factors (a) and the results are summarised in Table 8. The sequencing rule considered is FCFC (Sect. 4.1.1). From Table 8, it is evident that as the value of the multiplication factor increases, the delivery performance of the system also increases.

5 Conclusion

This article is an attempt to explore Industry 4.0 from the standpoint of manufacturing planning. In a complex job shop environment, most of the time, production managers struggle with the sequencing of jobs in dynamic conditions created by wide product variety, change in demand, volatile market conditions, uncertainty in supply, etc. Thus, a simulation-based POLCA integrated QRM approach is proposed. The proposed approach computes release authorisation time at each station for jobs. Thus,

Table 8 Delivery performance (%) for different due dates

Jobs	Arrival/week	Multiplication factor (a)				
		1.1	1.2	1.3	1.4	1.5
J1	500	70.43	78.03	82.81	87.48	90.88
J2	300	73.30	79.81	84.66	89.77	92.66
J3	200	69.93	76.51	82.69	87.14	90.45
J4	450	67.35	74.14	79.55	84.20	87.68
J5	300	72.05	78.54	84.01	87.90	90.98
J6	400	71.85	79.60	85.72	89.42	91.19
J7	250	67.57	72.09	78.16	82.40	86.11
J8	200	68.89	75.14	80.27	84.34	87.80
J9	500	70.15	77.63	83.97	88.39	91.44
J10	350	71.61	78.01	83.40	87.72	90.93
Delivery performance of system (%)		70.34	77.16	82.73	87.10	90.20

it can help to obtain an efficient job sequence in dynamic conditions. Also, controlling Work in Progress (WIP) inventory is a significant challenge. This approach simultaneously prevents the material flow in such a way that WIP inventories are almost negligible. In addition, the approach can help the production manager to commit suitable due dates to the customer for the required delivery performance of the system.

The delivery performance depends on the randomness of the arrival and service. If randomness is high, the chances to meet the due date are low. Here, the approach is tested for complex manufacturing scenarios having high skewness arrival and service distribution (exponential distribution), i.e., worst case. A simulation-based technique is used to evaluate the system performance. The simulation model automatically communicates with the central database of the system. This enables capturing any parametric changes like demand variation, job arrival pattern changes, capacity changes, etc. Moreover, the model can utilise the capabilities of CPS and IIoT. Further, the performance of the approach under dynamic conditions is analysed. Results show that improved system performance can be achieved by considering QRM and POLCA in dynamic conditions.

The present paper can lead to several potential extensions, as it is conceded for job shop. Though it is motivating to extend the current research towards other manufacturing systems, the present work does not consider the planning of raw materials, machine failures, and quality rejections, believing this will complicate the problem but bring it closer to reality.

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Sustainable Manufacturing

Study on Work Posture Assessment Using RODGERS Smart Form in Indian Firework Industries

V. Ajith, V. Arumugaprabu, R. Ramalakshmi, and N. Indumathi

1 Introduction

In India, the fireworks industry contributes substantially to the foreign exchange earned by the country. The firework industry consists of a number of units engaged. The industry is providing employment to people around the Sivakasi district [1]. Fireworks industries consume a large amount of raw material for conversion into final products. During the conversion of raw material to end product; material moves from one process activity to another, one room to another room and from one floor to another. Day by day, the production of fireworks is going up [2]. To achieve the target of production, the factory management is facing the challenges of safe, efficient and ergonomic material handling. This paper is based on the health problems faced by the workers in the fireworks industry associated with material handling operations [3]. Material handling is defined as an art of science for conveying, positioning, elevating, transporting, packaging and storing materials in standard methods. It states the movement of materials either manually or mechanically in batches or by separate item at a time inside the factory [4]. Those movements could also be horizontal, vertical or a mixture of two. During handling of materials, various manual works are involved [5]. The ergonomic-related issues of workers can be considered in likelihood ratings and severity ratings of the task which they are performing [6]. The workers involve themselves in their work for overtime in firework industries during festival seasons to increase production. So, it results in body fatigue, stress and other issues [7]. The work posture of workers while performing the task is also associated with the performance of industries [8]. Ergonomics also has a positive impact on production and

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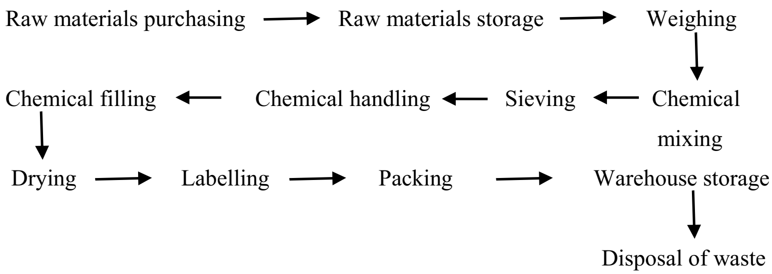
quality [9]. Manual lifting takes place almost in all working environments (industries, building sites, warehouses, hospitals, offices farms, etc.). Manual lifting can result in fatigue, and lead to injuries of the back, neck, shoulders, arms or other body parts. There are several ways of approaches available for controlling the stressors associated while performing manual lifting [10]. In case the requirement of manual operation can't be removed, then there must be a change in job requirement design through ergonomic aspects (e.g., modifying the layout of the job in physical format or reducing the working frequency or by the time duration of lifting) [11]. As a final solution, if redesign is not feasible, then the strain on that worker has been reduced by assigning the strain/work between two or more workers (e.g., lifting with help of a team).

2 Process Cycle in Firework Industries

The process that involves fireworks manufacturing is given below. The complete process involves only manual handling operations.



3 Manual Material Handling

Manual handling (MH) is defined as the process of handling or moving things by lifting, pushing, pulling, lowering, carrying, holding or restraining. Fireworks industries consume a large amount of raw material for making final products. The industries are using a large number of methods and processes. During the conversion of raw material to end product, material moves from one department to another manually. MH is the most common cause of occupational strain, fatigue, low back pain and back injuries due to manual performance.

3.1 Manual Handling Injuries and Illness

Manual handling involves the body to lift, carry, push, pull or support an object. A huge variety of injuries occur due to improper manual handling. Due to this, most of the common injuries occur to the back, hands, arms and feet. Typical injuries include back ruptured disks, sprained tendons and inflamed tendons, muscular problems and trapped nerves on the back.

4 Ergonomics

The word ergonomics is defined as art of science that fits between workers and their work. It states individuals first, assessing their term of confinements and capacities. It aims to make people confident that the job, machinery, required information and the working environment should suit people. Improperly designed workplace and work practice may result in musculoskeletal disorders (MSD) which results in causing pain, aches, swelling and poor performance. The most commonly affected parts are the back and arms.

4.1 Problem Identification

In the fireworks industry, most of the problems occur in manual material handling operations causing

- Heavy or awkward loads.
- Difficulty in tissue wrapping.
- Excessive use of force.
- Repetition and Twisting postures.

4.2 Case Study

The following data are collected from various employees working in fireworks industries based on questionnaire surveys regarding the health problems which they are facing in day-to-day life due to the involvement of manual handling operations.

S. no.	Year	Period	No. of injured	Issues	
1	2016	Jan–June	• 3	• Hand elbow	Hand elbow—Lifting excessive weight Wrist—Loading and unloading of weight Shoulder—Holding the weight on the shoulder Neck—Holding the weight in head Spinal cord—Lifting the weight and moving in a bending position Knee—Lifting the weight in the staircase/sloping area Ankle—Slipped during walking with load Back pain—Frequent bending to lift the load Muscle pain—Excessive lifting of load/Over work load
			• 4	• Wrist	
			• 3	• Shoulder	
		July–Dec	• 5	• Neck	
			• 5	• Spinal cord	
2	2017	Jan–June	• 6	• Knee	
			• 7	• Ankle	
			• 6	• Wrist	
		July–Dec	• 5	• Back pain	
			• 3	• Hand elbow	
			• 3	• Muscle pain	
3	2018	Jan–June	• 6	• Wrist	
			• 4	• Knee	
			• 4	• Shoulder	
		July–Dec	• 5	• Neck	
			• 6	• Shoulder	
4	2019	Jan–June	• 9	• Back pain	
			• 4	• Hand elbow	
			• 4	• Muscle pain	
		July–Dec	• 7	• Ankle	
			• 5	• Knee	
			• 5	• Muscle pain	
5	2020	Jan–June	• 2	• Spinal cord	
			• 4	• Back pain	
		July–Dec	• 4	• Wrist	
			• 3	• Ankle	
			• 3	• Hand elbow	

5 Assessment Tools

Ergonomic assessments can also be defined as workstation assessments, help to ensure that a worker's workplace is ergonomically developed/designed to minimize the rate of risk and help to maximize production rate. Ergonomic assessment can be done in the work postures using computer-aided ergonomics assessment tools like

- RODGERS Smart form

  The purpose of the assessment is

- To help the return of an injured worker to work by promising that their workplace is designed to minimize any annoyance.
- To make ergonomics an ongoing process for identification of risk and reduction of risk based on the objective and scientific way of analyzing the workplace.

5.1 RODGERS Smart Form

RODGERS smart form is used to conduct the muscle fatigue assessment of the human body of the worker. Effort level of the muscles can be rated as 3 levels (1) Light, (2) Moderate and (3) High. It is used to generate force with respect to muscles; the physical or muscle fatigue needs to be declined. It ends in continual exercise but abnormal fatigue may occur by barriers or interference with the different levels of muscle contraction. Table 1 indicates the assessment of RODGERS smart form muscle fatigue of the following body parts.

6 Ergonomic Improvements

In general, the change in ergonomic enhancements is set to improve the fit between expectations of the work mission and the abilities of the workers. There are many options available for improving a particular manual handling task. It is a little more complicated to make choices regarding which improvements will work best for a particular task. There are two types of ergonomic improvements.

6.1 Engineering Improvements

Engineering improvements include modifying, rearranging, providing or replacing tools, redesigning, equipment, workstations, parts, processes, packaging, products or materials.

Table 1 Fatigue assessment

Region	Light (1)	Moderate (2)	High (3)
Neck	Neutral neck: head turned partly to side; back or forward slightly; back leaning forward 0–20 °	Head turned to side; head fully back; head forward about 20 degrees	Same as moderate but with force or weight; head stretched forward (chin tucked into chest)
Shoulders	Neutral arms; arms slightly away from sides; arms extended with some support	Arms away from body, no support; working overhead or behind	Exerting forces or holding weight with arms away from body or overhead
Back	Standing; sitting with lumbar support; leaning to side or bending slightly; arching back	Bending forward; no load; lifting moderately heavy loads near the body; working overhead	Lifting or exerting force while twisting; high force or load while bending
Arms/elbows	Neutral; arms away from body; no load; light forces lifting near body; no twisting	Rotating arm while exerting moderate force	High forces exerted with rotation; lifting with arms extended
Wrists/hands/fingers	Light forces or weights handled close to the body; straight wrists; comfortable power grips	Grips with wide or narrow span; moderate wrist angles, especially flexion; use of gloves with moderate forces	Pinch grips; strong wrist angles; slippery surfaces
Legs/knees	Standing; walking without bending or leaning; weight on both feet	Bending forward, leaning on table; weight on one side; pivoting while exerting force	Exerting high forces while pulling or lifting; crouching while exerting force
Ankles/feet/toes	Standing; walking without bending or leaning; weight on both feet	Bending forward, leaning on table; weight on one side; pivoting while exerting force	Exerting high forces while pulling or lifting; crouching while exerting force

6.2 Administrative Improvements

Administrative improvements would consider alternating heavy tasks with light tasks, providing a variety in jobs to eliminate or reduce repetition (overuse of the same muscle group), adjusting work schedules, work pace or work practices, providing recovery time (short rest breaks), modifying work practices within power zone and rotating workers through jobs that use different muscles, body parts or postures. This can be done by putting into place the appropriate engineering improvements and modifying work practices accordingly.

7 Ergonomic Assessment and Suggestions

From the data collected from the industry, it was found that most of the industrial accidents and health hazards occurred due to the performance of manual handling of materials in industry. In order to control these problems related to work, change in the work posture should be done in the organization. Conducting risk assessment using the various ergonomic assessment tools will reduce the risk level of the workers and increase production.

7.1 Raw Material Handling

Work: Unloading raw materials bale (chemicals, tissue paper, boxes, outer shell of cracker, etc.) from the truck and movement of those items to the stockyard area.

Difficulties:

- Bending and dragging the bale (weight of 100 kg).
- Movement of material in the slope may have a chance of slippage.

Suggestions:

- Use of roller setups to unload the material.
- Provide trolleys to move the material from the unloading platform to the stocking area.

From Fig. 1, it defines clearly that the accepted level of force to handle the load is 1414.5 N as per ergonomic norms but in fireworks industries, the force given by workers to handle the load is much higher than the accepted value both in normal and slop platforms.

3D SSPP software analysis results:

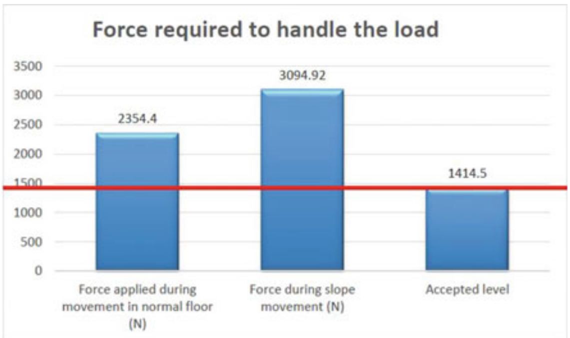


Fig. 1 Force required to handle the load

3D SSP software is used to predict the static strength of workers which is required to perform a task. By entering the required value, the software provides the approximate work posture in Fig. 2 to perform the job in a proper manner.

Suggestions: Design of the new bale handling trolley as per the requirement and standards reducing the ergonomics-related problems in bale handling.

From the study, it is observed that there is a need to implement a new technology for carrying out the bale from one area to another within a short distance. Therefore, a mini trolley was designed to handle the packages that would prevent the workers' manual lifting and carrying. Figure 3 is a design of a trolley which was drawn using AUTOCAD software. Figure 4 shows the simulation design of the trolley which was done by using ANSYS software and finally Fig. 5 is a fabricated trolley.

7.2 Technical Improvements

- Both men and women workers can easily operate the trolley, since it is designed in such a manner. No special training is required.
- It is capable of carrying loads up to 200 kg per time. Therefore, it helps to minimize the worker's workload. It also consumes less time.
- Once the load is placed in the trolley, it can be moved vertically with the help of a rotating mechanism which prevents the workers from bending lower to pick up the load.
- It can be operated by both men and women with minimum effort to carry bales from one place to another.

Fig. 2 Picture of data for ergonomic analysis entered in 3D SSPP software

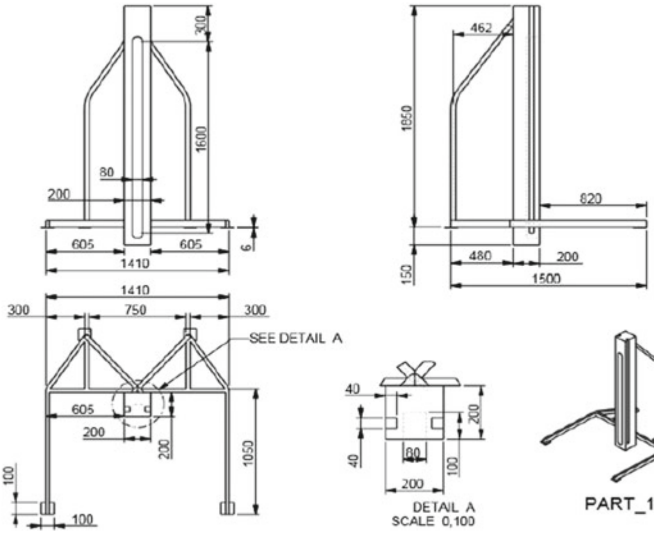


Fig. 3 CAD design of trolley

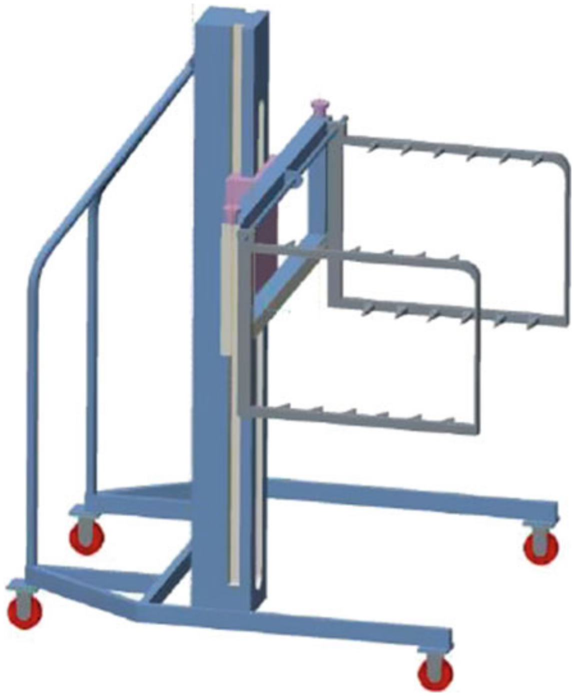


Fig. 4 ANSYS design of trolley

Fig. 5 Fabricate trolley

8 Conclusion

Accidents, injuries and illness are common for all industries. To reduce these risk, statistics and analysis were performed using risk assessment and ergonomic assessment tools like the RODGERS Muscle fatigue assessment tool. On analysis, it was found that most of the work postures have a potential risk of causing accidents and illness to the workers. To control or minimize those injuries and illnesses of the workers, related to work postures, a risk assessment strategy has been performed. As a solution, a change in work posture has been recommended to control the potential risk. In future, if the recommendation provided by this study is implemented in fireworks industries, the reported risk will reduce or even may be nullified. From the survey taken from workers regarding ergonomic illness, most of them reported that the illness was due to the manual lifting of load while transferring raw materials or finished goods from one place to another area. Thus, the proposed study concludes the use of proper equipment that fits the workers' requirements while performing physical work. Proper manual material handling operation helps in eliminating both acute and chronic disorders due to work posture. Therefore, this research helps in improving the workers' life while working and also leads to improving the product quality in aspects of health and safety.

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Developing a Line of Sustainable Seashell Jewellery and Proposing a Manufacturing Loop to Improve Upon Traditional Processes

Parag K. Vyas and Nitya Vyas

1 Introduction

The jewellery industry in India comprises massive chains and systems of manufacturing linked to each other by microprocesses. Each of these processes requires a very specific set of raw materials and tools. For example, soldering a piece of gold jewellery will require flux, cut solder pieces and tools such as borax plate and cone, soldering brick, blowtorch, tweezers and soldering clamps.

The sector relies heavily on the availability of precious and semi-precious gemstones and metals. The most commonly used metals in production include gold and silver. They are often alloyed with materials such as copper, zinc, platinum and palladium to achieve a vast array of different properties that are specifically required for an article of jewellery. Additionally, materials like leather, bone and horn, brass, beads, resin, terracotta, stainless steel, clay and shells are used to make jewellery [1]. Base metals like brass and copper are often plated with metals such as gold and silver to create a certain look and finish for the more affordable collections. Sustainability in the jewellery industry is dependent on both raw materials and the manufacturing methods used in a production line. When the material is obtained through sustainable sources and is used efficiently to avoid wastage, it contributes to a sustainable manufacturing loop [2].

Mother of pearl shells are natural, and biodegradable materials that can be introduced to make entire articles of jewellery instead of just embellishments such as buttons or brooches have been in common circulation so far.

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2 Need Statement

Metals used in jewellery can be remelted and reused and hence fall under the category of recyclable materials. Alloys can be chemically separated using processes such as liquation. Repeated liquation is also used as a method to purify metals. However, this in itself does not ensure that the production process becomes a sustainable one. Other factors such as the sourcing, pre-production processing and life cycle of the product also affect the sustainability of an article of jewellery [3].

Extraction processes to get metals from ores are lengthy and elaborate. Most of these processes involve heat treatments, chemical reactions that lead to a lot of water wastage and contribute to pollution on multiple fronts. Moreover, the process of obtaining the ores themselves is harmful to the environment when carried out in excess. Aggressive mining of both metals and gemstones contributes to environmental degradation, and proceeds to make the very root of jewellery production unsustainable. Therefore, it is suggested to control and regulate the amount of metals and gemstones being utilised in everyday production.

Production of jewellery involves skilled implementation of manufacturing processes using specifically designed tools such as piercing saw blades and drills. Intricate work demands hours of intensive labour and competent operation of these tools. A novice jeweller requires practice to become a master jeweller and wield tools with precision [4]. Over time, these tools start to show signs of wear and start performing at suboptimal levels. At this point, they need servicing and some parts need replacement. Due to the lack of knowledge on the shop floor, these tools often end up in the dump instead. Items like saw blades and drill bits are constantly breaking, which can only be repurposed in very limited ways. Along with the tools, dust from precious metals is also lost—leading to irretrievable losses. This loop needs reconstruction [5].

Apart from tools, gemstones also need to be handled with care. Once broken, gemstones cannot be put back together. The broken pieces are either ground and polished into a gemstone of smaller size or ground to form a powder which may or may not be utilised in other operations. The gem sizes and the setting process will also benefit from reform.

The need statement covers multiple aspects of the current production cycle, and the key issues it focuses on include

1. Excessive mining of metals and gems;
2. Lack of knowledge on tool maintenance and upcycling;
3. Lack of focus on the life cycle of jewellery articles.

3 Background Study

Mother of pearl is an iridescent composite material produced by molluscs in their inner shell. It is the same material with which the outer layer of pearls is made.

Fig. 1 Abalone shells

It is a combination of calcium carbonate, organic substances and water. Different wavelengths of light passing through this iridescent coating brings out different colours when viewed from different angles and directions. It is also known as 'nacre'. This natural shimmer is pleasing to the eye and appealing to the general population [6].

Very few molluscs can produce pearls while many more species produce the layers of mother of pearl in the shells making the material more readily available.

The seashells explored in this study include

1. White, yellow and black coloured Mother of Pearl shells;
    1.1. A white, cream or off white shell base with a violet to green iridescence;
    1.2. A slight yellow base with violet to green iridescence;
    1.3. Either jet or grey-black shell base with a violet to green iridescence;
2. Pink, red or coloured natural as well as dyed Mother of Pearl shells;
    2.1. Bands and patches of pink, red and peach arise on a white shell surface;
    2.2. Multiple colour options are available with dying
3. Abalone shells (Fig. 1).
    3.1. A specific type of shell obtained from the gastropod shellfish, abalone also has a mother of pearl coating.
    3.2. The atypical range of colours visible give it extra appeal.

Being a natural material, no two shells are ever the same. Various properties of these shells help determine which ones can be utilised to make which article of jewellery. The properties that need to be considered include

1. Lustre and colours
   1.1. Highly lustrous pieces are used for articles which hold central focus such as pectorals and brooches while the comparatively less lustrous pieces can be utilised for earrings and bracelets.
   1.2. Differently coloured shells can be used in coordination to create visually interesting contrasting pieces in inlays and double inlays. (Fig. 2)
2. Size and shape
   2.1. Depending on the size of the shell, multiple permutations of pieces can be adjusted on one base.
   2.2. The curved surface of a seashell is hard to work with. Depending on the depth of the seashell, different ranges of cross-sectional curves are marked. The designer and maker have to plan which parts of the seashell would be suitable for a particular piece depending on these marked areas.
3. Thick and thin shell parts
   3.1. The thickness of the shell varies within the shell at different points. These need to be measured and pieces need to be drafted in accordance with

Fig. 2 Contrast between two semi-finished pieces of black and white Mother of Pearl during development

respective tolerances keeping in mind that the shell will be susceptible to breakage once it's been cut out.

3.2. Thinner parts work better for standalone pieces as compared to thicker parts which are more appropriate for inlays and intricate piercings.

Apart from the wastage of broken and worn-out tools, traditional manufacturing processes end up being wasteful with materials as well. For example, metal dust that is generated after sanding cast jewellery is generally not retrieved beyond a point. The gemstones that have been ruptured to the point of no return will eventually lose application and value. While diamonds are typically resistant to chipping, softer stones like emeralds are prone and susceptible to it. Sizes can be accurately regulated once gemstone cleavage is taken into consideration [7].

4 Methodology

Primarily, data collection has been qualitative with the exception of weights of seashells which were recorded over the years for the drafting of designs. The development of this line took place over the span of 3 years, during which various observations were made on the shop floor. Simple deductions followed these observations.

During the development, experiments pertaining to finishes and other processes were undertaken. Pieces were displayed in private showings to people from various fields. Feedback received were incorporated into the study.

Methodology with the system diagram depicting proposed/tested production loop is illustrated in Fig. 3.

5 Proposition of a Line of Sustainable Seashell Jewellery

After taking into consideration the factors discussed above, the line jewellery was formulated. The main aims included [8]

- Ensuring sustainable procurement of shells;
- Replacing regular metal and gem jewellery with a natural organic material—mother of pearl;
- Reducing the overall usage of metals;
- Regulating the size and number of gems;
- Keeping tool life and servicing in mind;
- Making sure that the line's sustainability goals are met end to end.

Main features of the jewellery line included

- Pierced and inlayed pieces of seashells paired with some precious/semi-precious metals;
- Simple motifs used to design each piece (Figs. 4 and 5) [9];

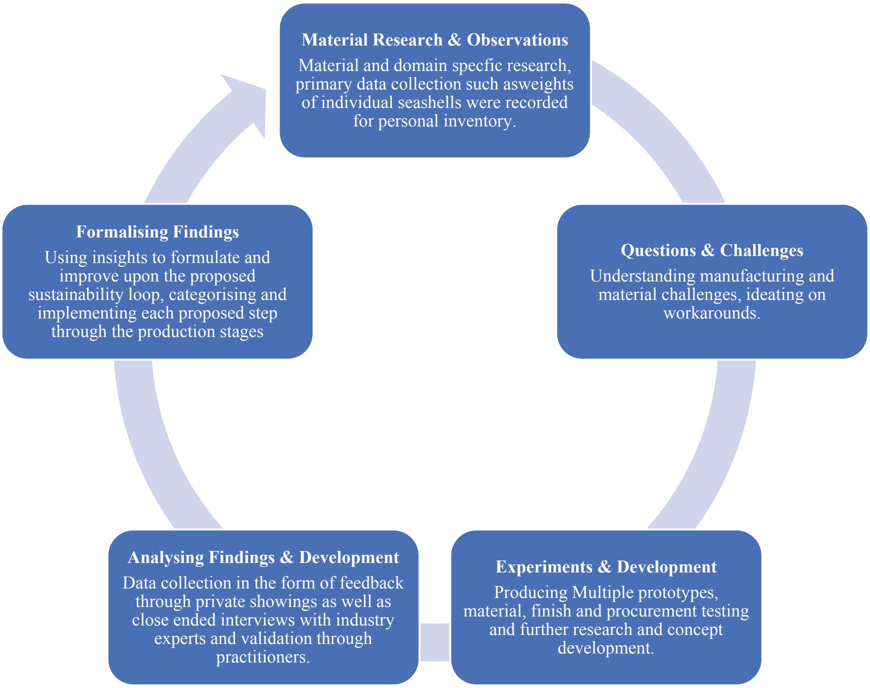

Fig. 3 System diagram depicting proposed/tested production loop

Fig. 4 Simple motif being prepared for inlay during manufacturing

Fig. 5 An example of a collection from the line; a pendant, earrings and finger ring

- Inlays, double inlays and piercings for decoration;
- Supremely finished, lustrous pieces—each piece was 'superfinished';
- Carefully sized gems as additional ornamentation in some pieces;
- Most of the making relies on a competent craftsman, with the exception of a few mechanised processes.

Some manufacturing challenges included

- Maintenance of a long-term loop for the sustainable sourcing of materials;
- Craftsmen training and quality control;
- Developing a design framework/template which suits the properties of different shells;
- Refining traditional jewellery manufacturing processes to adapt to the new material.

6 Proposition of a Process

To address the loopholes in the current production system, the introduction of a set of procedures for pre- and post-production will ensure that a sustainable process loop is maintained.

1. Pre-Production
    1.1. Ethical and Sustainable Sourcing
    1.2. Analysing and categorising shells according to aforementioned properties such as colour, lustre, shape, size and thickness to determine the most suitable piece for each article.
    1.3. Pre-planning incisions and placement of designs on shells must be done to ensure that it is completely utilised and any loss is avoided. The weak and strong points on the shell must be noted to avoid any misplaced designs and breakage of pieces later.
2. Production
    2.1. Regulating the size of gemstones to be used will reduce the probability of the stones breaking.
    2.2. Replacing a significant part of metal or gem jewellery with an organic material to reduce the metal in production lines.
    2.3. Regulated tool servicing.
3. Post-Production
    3.1. Tool Servicing will allow a lot of otherwise condemned tools to be upcycled and repurposed.
    3.2. Life cycle analysis of components would include knowing where each piece would go. The jewellery made out of shells will be completely biodegradable. However, if the wearer wishes to preserve it, it will also last multiple lifetimes with good upkeep.
    3.3. Revamping broken and worn-out tools. For example, delicate drill bits that lose their top during drilling operations can be sanded into a sharp top and used as tops of point burnishers.

7 Limitations

Due to the lack of formal research and empirical evidence recorded in the jewellery industry, accurate data about losses is not available or unreliable if available.

A part of the sustainability aspect in the proposed process loops relies strongly on sourcing of the materials being used, and hence needs a lot of consideration.

Since development on the line of seashell jewellery is ongoing, and has found a niche segment with only a few patrons so far, some processes need to be partly mechanised.

8 Merits and Contributions

- The paper introduces an otherwise usually overlooked sustainable material in a new form and context.
- It regulates the use of metals and gems—by weight as well as by size, making use of an organic material in conjunction with materials that are already widely circulated, thereby reducing the impact of aggressive mining on the environment.
- It introduces simple but effective methods of streamlining traditional practices with sustainable ones.
- It brings back the importance of a craftsman in the manufacturing of jewellery as compared to mechanised processes, and hence contributes to healthier cooperation between the designers and craftsmen.
- It allows upcycling and refurbishment of tools which would have otherwise contributed to waste.
- The study takes into consideration the nuances of jewellery design, roots of Indian jewellery by incorporating motifs that have heritage value.

The aforementioned research and processes enable a new line of development to take place in the Indian jewellery sector and give way to a movement that promotes handwork.

9 Future Directions

This study holds great scope in terms of creating a niche market for the artisanal value of jewellery.

A lot of value is added to the material through skilled labour. This study will help restore the pride in handwork in the Indian Jewellery Sector along with further development.

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Sustainable Manufacturing Innovation for Woodturning Handicrafts

Rumpa Reshmi Munshi

1 Introduction

In the phrase "sustainable manufacturing", the word "sustainable" has different meanings in different contexts. In a paper by Allen & Hoekstra, "Toward a definition of sustainability", it has been defined as a method of collaboration with nature that would produce an innovative positive effect. It has also been described as a requirement to gain returns on a long-term investment [1]. Sustainability may be achieved through an integrated approach that links a community's economy, environment, and society. Rosen and Kishawy believe that to make manufacturing sustainable, economic, environmental, or societal objectives must be balanced, and integrated with supportive policies and practices [2]. It may be inferred from these definitions that innovation in manufacturing may be termed sustainable when it co-exists with nature and is accepted by a community because it balances its economy, systems and practices. The Indian handicraft sector is made up of such communities, which have their defined environment and society. It is governed by the Ministry of Textiles and Ministry of Micro, Small and Medium Enterprises or industry [3, 4]. Each handicraft cluster has its systems and practices that co-exist with nature but is often out of balance due to economic unsustainability. The handicraft industry, therefore, requires innovations that benefit the business and bring economic viability.

This paper presents an innovation in the field of handicraft, which is an environment-friendly industry. The study is a part of doctoral research to understand the sector's economic gap and find sustainable methods to overcome it. The research was exploratory in nature and based on the case of the turnwood lac-ware of Channapatna in Karnataka, India. The investigation started with ethnographic study and field observation to understand the artisans and make a life cycle analysis (LCA) of their products. Further, a consumer survey highlighted the need for a change in

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physical forms and attributes of the products made using the craft [5]. Based on consumer demands, a study was done to understand the possibilities of new forms for the cluster, and accordingly, an intervention was made in the manufacturing technique. This paper presents the innovation, the related use of TRIZ to achieve it, and an assessment in the field to determine the sustainability of the intervention.

2 Handicraft Types: Decorative and Industrial

India has a large population of artisans with rich handicraft knowledge and skills. The demography, economy, and capabilities are conducive to a prospering handicraft industry. The handicrafts made are usually unique to a region, but similar craft may be found in other areas when machinery is involved in craft making. Handicrafts are artisanal products, either made entirely by hand or with the help of machines but with substantial manual contribution by the artisan. The products have unique distinguishing features owing to the material being used, and its aesthetic aspects may have cultural or religious significance with varying functionality and purpose [6]. Based on the manufacturing technique, the crafts may be called decorative, when handmade, and industrial, when machines are used. Since decorative crafts are made by hand, no two pieces will be identical. Skills like hand carving, hand moulding, hand embroidery, or hand painting techniques may fall under this category. Industrial craft allows artisans to make multiple identical pieces within one production cycle. Skills like woodturning and pottery turning are examples of industrial craft [7]. The craft of turnwood lac-ware of Channapatna falls under the industrial category.

3 Field Study

3.1 About Channapatna

Channapatna is a township in the district of Ramnagara, located between the two biggest metropolitan cities of the state of Karnataka, India, namely, Bengaluru and Mysore. The settlement has a population of approximately 70,000 and is spread over an area of 12.87 km^2. The town is home to an estimated 2500 artisans, who make woodturning lac-ware products like toys, home décor and jewellery, for a living [8]. These are made from the wood of Wrightia Tinctoria tree, locally known as "*Hale Maara*" and found abundantly in the region.

3.2 The Manufacturing Process

The Oxford dictionary defines woodturning as a mechanism for shaping a wooden workpiece by removing small amounts of it with a chisel, while the piece is being rotated by a lathe machine. A lathe is a simple machine that rotates a workpiece against a fixed cutting tool to remove material uniformly and give it the required size and shape [9]. The wood is securely held in position on the machine on its long axis and an external chiselling tool is held perpendicular to the wood [10]. The Channapatna artisans colour the shaped wood with pre-made colour sticks of lac obtained from insect species named Tachardia Lacca or Kerria Lacca. These sticks render their colour to the wood piece on melting due to the friction from turning. The workpiece is later polished using Palmyra leaves of plant species Pandanaceae, for even spreading of colour and shine. This technique of craft has existed for more than 200 years using the same turning methods, either employing a bow lathe or more commonly the simple speed lathe [11].

3.3 The Lathe Machine Operation at Channapatna

The speed lathe of Channapatna is a hand-assembled machine (Image 1). The arrangement may be divided into three parts: the electronic motor that gives power to the machines; the wheel and the axle that connects multiple lathe spindles for assembly

Image 1 A lathe spindle

Image 2 Cup chuck

line work; and the main body or the lathe spindle, where the workpiece is held for turning. The 3 HP motor is the only automated component that gives power to rotate 10–12 machines, simultaneously. In the case of stand-alone lathes, a ½ HP motor is more than sufficient. The wheel and the axle are fixed over the working table. They are rotated by the motor using a rubber belt. In turn, the axle transfers the rotatory motion to the main component, the spindle, via rubber belts. The rod-shaped spindle is fixed on a 60 cm long metal bed that is screwed securely to the worktable. The spindle is a 20 cm long iron rod, placed on the left-hand side of the bed, as the artisans are primarily right-handed. It is elevated from the bed with the help of a sturdy iron frame at a height of 15 cm. The wooden workpiece is mounted on the spindle for rotation, with the help of a holder-cum-connector called chuck or "*Chandrikay*" in the local language (Image 2). A chuck is made up of casted metal, like aluminium or steel, and has a cylindrical or cup-like appearance, which is hollow at either end. The chuck is mounted at one end of the spindle and screwed securely. The lathe spindle together with the chuck is known as the lathe head. The workpiece is gently hammered into the lathe head to fit the hollow, on the other end of the chuck. This process aligns the spindle, chuck and workpiece in a single axis and renders a symmetrical shape to the wood products during turning of the lathe. This is understood as a single-axis rotation.

A review of literature on turning shows that an automated or industrial lathe can create different forms through techniques like asymmetrical, segmented, wet wood, and spiral turning [12, 13] (Images 2 and 3).

However, the assembled lathe of Channapatna is not geared to perform such tasks as it lacks computerized control, lacks a tailstock to provide extra support to the workpiece from the other end, and has only a fixed chuck working on a single axis. These circumstances prevent the artisans from exploring new options in form and restrict the Channapatna cluster products to symmetric forms (Image 3). Contrarily, the craft sector requires novelty in aesthetics to keep its retail business sustainable [14, 15].

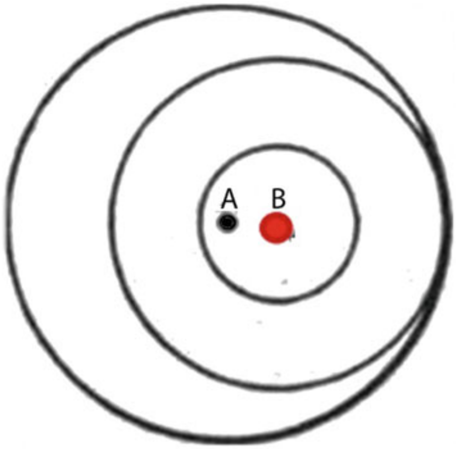
Image 3 Symmetrical product from field

4 Innovation

4.1 The Design Considerations

The innovation requires introducing at least one new method of turning to achieve new forms. In order to give the artisans more scope to explore forms in turning, without any drastic change in their environment, equipment and required skill set, eccentric turning was considered as a quick win to produce asymmetric forms. Eccentric turning is a technique in turning achieved by creating a new axis that is offset from the central axis (X and X′) [16]. The rotating workpiece moves along a wider circumference around the spindle, when it is on the offset axis (Image 4). This causes more material to be removed from one side of the workpiece than from the other, thereby creating asymmetric shape. The challenge was to determine how to achieve eccentric turning in the current system, where the chuck has a fixed axis. The intervention was to add a new chuck that would allow the artisan to shift the workpiece to different offsets to achieve different results in asymmetry.

Image 4 Offset axis diagram



The literature lists the general design considerations for the new chuck: (1) capability to hold workpieces of different sizes firmly, accurately, and securely, (2) the ability to resist forces while turning is in progress—both centrifugal and applied, (3) leave the least amount of marking and scoring on the workpiece, (4) understanding the relation of the workpiece to the chuck that is holding it, (5) the material it is made of, the purpose, and the impact on it of the task being undertaken, (6) the relation between the machine and the workplace, (7) a design that is ergonomic and ensures the safety of the artisan without affecting their performance, (8) ease of maintenance, (9) ensuring that controls and displays are self-explanatory, (10) retaining the circular shape for ergonomics and fluidity of motion [17–19].

Further requirements were collated from the views of experts and through field observations. The learnings were that the weight of the chuck should not be more than 2.5 kg for better stability, the material of the chuck should remain the same as used today in the cluster, the scale marking should be in millimetres, and the basic chuck design and handling methods should remain the same. Based on the above learnings, it was decided that an existing cup chuck needed to be modified to allow the shifting of axes. In order to achieve this requirement, a TRIZ contradiction matrix was used.

4.2 The TRIZ Matrix

TRIZ or the "Theory of Inventive Problem Solving" is a problem-solving tool based on data, developed by Altshuller and his team [20]. The contradiction to be resolved by applying the TRIZ method was improving "productivity" while preserving "ease of operation". The TRIZ matrix provided the following general principles: segmentation, mechanic substitution, nested, and preliminary actions [21]. Re-interpreting the principles in view of the above guidelines, it was decided that the current chuck could be split into two segments to provide different axes (segmentation). The two segments would require to be linked using structured moveable parts (mechanics substitution). Hence the segmented pieces of the chuck were connected to each other using circular plates for ease of rotation. Finally, to manipulate the segments quickly (preliminary action), a sliding mechanism was introduced on the disc with easy-to-use screws. A millimetre scale was also etched on the chuck. After trial and error, the new chuck was made field ready. Images and exploded view diagrams are placed to provide a visual reference for the innovation (Images 5, 6 and 7). The innovation would prove to be sustainable only after acceptance by the artisans of Channapatna.

Image 5 Exploded view of asymmetrical chuck

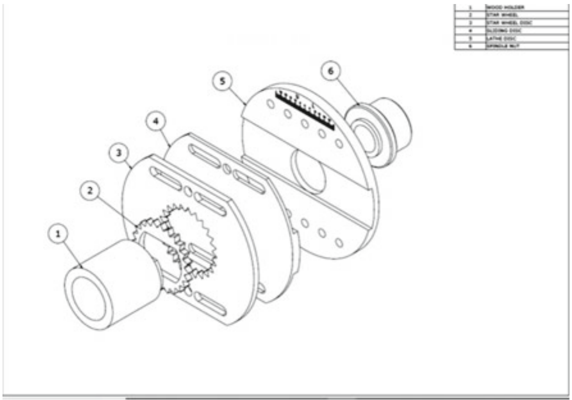


Image 6 Top View of asymmetrical chuck

Image 7 Side View of asymmetrical chuck

5 Assessment

The assessment questionnaire was created based on the technology acceptance model of Davis [22] and through the triangulation method with experts from the field, who have been training artisans and students on turning for more than 20 years. The experts were from the Institute of Wood Science and Technology, Bengaluru, which has a lathe training setup, Maya Organics, an NGO and noted hub for making the woodturning toys at Channapatna since the last 25 years and Seiger Spintech Equipments Pvt. Ltd., which makes industrial lathe accessories and has their own simulation and trial procedures. The focus was to find out the perception of the artisans towards the use of the new chuck. The broad areas of assessment consisted of attitude, competency, ergonomics, and barriers. The methodology adopted was to implement the device in the field for a period of one week and observe as well as interview the artisans, to note the findings of the above assessment criteria. The case was administered to 35 highly skilled artisans and the design specifications for three asymmetric forms were given, along with the new chuck.

The "***attitude component***" of assessment was ascertained based on studying the perception and willingness of the artisan to work on the new chuck. It was determined through variables like "Are the artisans willing to try the new chuck as a challenge, does the new type of turning intrigue them to put effort, does the new level of turning excite them, are they interested in spending time to practice, are the artisans open to learning the new method, are they willing to put in extended hours of work and practice on it repeatedly". The results revealed that almost all artisans agreed that it was a "new type of turning" (90.2%), and most (77.1%) were willing to take on the challenge, and “practice on it repeatedly”, with “extended hours of work” and found it to be “exciting work”.

The “***competency***” of the artisan was based on their comprehension—whether the artisans were able to build their existing knowledge and skills while using the new component to create asymmetric forms. The process of using the chuck has been ascertained based on 17 variables. The artisans felt that the most essential was to know what size of wood to choose to achieve the final product size as per the specifications since it was difficult to predict how much material would be lost in asymmetric turning. They indicated that they could easily work with a maximum shift in the axis of 10 mm.

The “***ergonomics***” of interaction with the new chuck was built on five variables based on the steps in the process—“mounting the chuck to the lathe, stopping the chuck from turning mid-activity, changing the screws of the chuck to shift the plate for eccentricity, identifying the amount of vibration during eccentric turning and ease and safety while handling the chuck”.

The primary challenge faced by the artisans was that the “vibration was more than they were used to” and it needed more practice to get adjusted. This was followed by “stopping the chuck mid-activity” and “changing screws of the chuck to shift the plate for eccentricity”, for which they found workarounds later. All found it easy to use the chuck without hurting themselves.

The “***barriers***” were determined by a set of eight questions, such as additional time and effort taken, compatibility of the chuck with an existing machine, more wastage, higher costs, and perception of acceptability and profitability of the new designs. The main barrier was the additional time taken and the higher cost, but they felt that the profits would be higher, and the same machines could be used.

6 Conclusion

The above study presents how innovation may be implemented in a small or medium-scale industry to achieve novelty in product design for the evolving consumer market. Handicraft by nature is eco-friendly and sustainable; however, the industry needs constant upgradation to ensure better economic viability. The implementation of new ideas in this sector becomes a challenge, as the artisans are usually reluctant to change. Yet they are looking for quick financial gratification. This new chuck brought in excitement and promise of new aesthetics and higher sales, and hence the artisans accepted the method readily. Images are placed of products that have been made by symmetrical and asymmetric turnings to provide visual reference to the change in form (Images 8 and 9).

Since the artisans work in an assembly line, the designs could be conceptualized as distinct symmetric and asymmetric components, with the highest skilled artisan working on the latter. This would reduce the material wastage and time that the artisans were apprehensive about. It would also give a fresh visual appeal without further increasing the cost of production. The industry would not require as much

Image 8 Cat in symmetrical chuck

investment on the new chuck, as only a few artisans would work on the asymmetrical components (Image 9).

The scope of work in future is to implement the same in production. Artisans would need to practice to overcome the teething issues of working with a new component and form. The innovation would be completely sustainable once it is integrated into the system over a period.

Image 9 Cat in asymmetrical chuck

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Implementing Industry 4.0 and Sustainable Manufacturing: Leading to Smart Factory

Archit Gupta and Princy Randhawa

1 Introduction

Manufacturing has been changed from batch production and mass production to personalized production through the transformation from the first industrial revolution to the current era of the fourth industrial revolution known as Industry 4.0. This revolution aims to leverage the connected capabilities and intelligence of distributed socio-technical systems, including people, computer-aided design and engineering tools, information systems and sensor networks, robotics, advanced manufacturing, etc. to improve productivity, quality, flexibility, safety and sustainability across manufacturing enterprises, and production environments [1].

This paper materializes spot welding to portray the process of increasing production, preventive maintenance, and energy saving. Spot welding is a process of welding two or more metal sheets together by applying pressure and heat with the support of a high electric current, forming a welding area.

2 Motivation

An empirical study was conducted in Switzerland in 2020 with 39 Industry 4.0 experts from various polished companies [2]. The responses which had the most frequency to the question: "What others do not know about the specifics of implementing I4.0?" were "It is profitable" and "It is possible to integrate existing devices onto processes". 23% of respondents gave these two responses. Slightly fewer indicated that "System solutions are available" (18%), "It is scalable" (14), and "What technologies exist"

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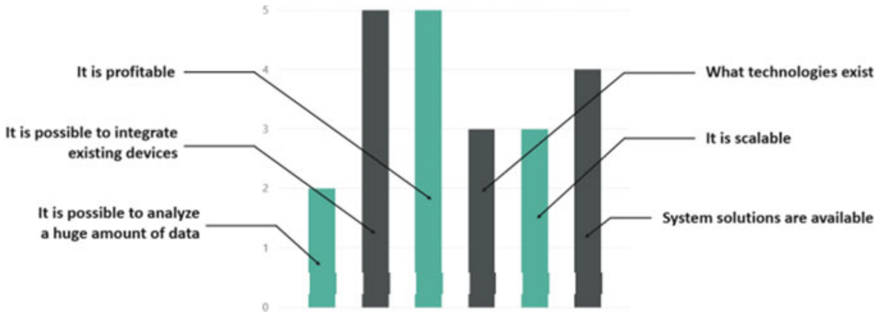

Fig. 1 Lack of knowledge about 14.0 and implementation [2]

(14%). Figure 1 shows the detailed distribution of the responses. This suggests that Industry 4.0 is yet to be properly implemented and has to undergo multiple alterations.

A study by UNDP states that globally more than 78% of total final energy consumption is sheltered by fossil fuels. Modern renewables only contributed 10.3% with solar and wind power. The energy sector still majorly contributes to greenhouse gas emissions. Reducing energy consumption decreases the carbon emission in the environment. This paper points toward two major advancements required in the field of automation in the near future are energy-saving and preventive maintenance [3, 4] (Fig. 2).

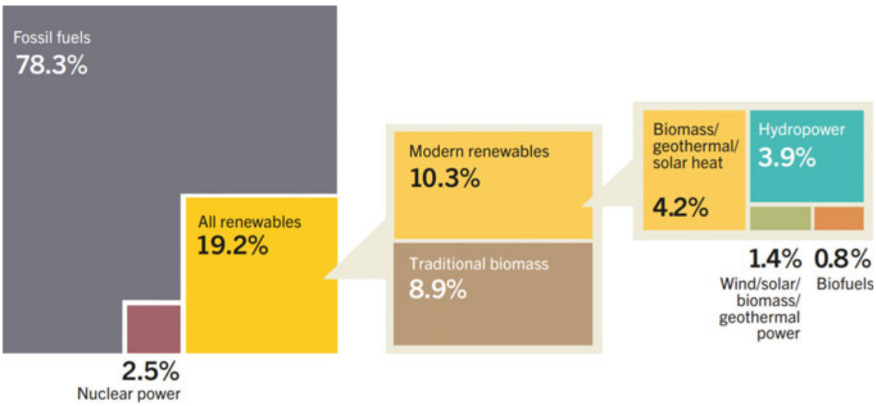

Fig. 2 78% of total energy consumption is sheltered by fossil fuels [4]

3 Methodology

Industry 4.0 is based on the interconnectivity of nine industrial pillars. Production processes are improved by the manufacturers using these pillars. In addition, the production relationship between the man and the machine is increased and made reliable (Table 1).

Implementing Industry 4.0 in this project has been carried out in certain steps which start from the basics of operation and end in decentralized data across platforms with the help of industrial Internet of Things.

3.1 Implementing Industry 4.0

Breaking Industry 4.0 into six steps, these steps are the basic building blocks of a smart factory. These are crucial for implementing Industry 4.0 (Fig. 3).

Table 1 Industry 4.0 pillars

Industry 4.0 elements	Description
Internet of things	Used for taking real-time decisions with the help of device interaction and exchanging data
Big data	Taking real-time decisions backed up by data collection and analysis from multiple sources
Autonomous robots	Robots are increasing flexibility and efficacy in various areas of production
Simulation	Testing and optimization of machines before physical production
System integration	Vertical and horizontal integration between production services creating a universal network of machines
Cybersecurity	Making communication reliable for machines within the network and making them secure from external threats
Cloud	Data from the cloud is used to drive more services for production systems
Additive manufacturing	3D technology is being used for customizing products in small quantities, enabling proto designs
Augmented reality	An application used in warehouse management by enhancing real-life world environment

Fig. 3 Industry 4.0 flow

Fig. 4 Data processing flowchart in python

- Data Collection: Collecting data from PLC and sensors. The data is then transferred to the server via the cloud.
- The data is collected from the programmable logic controller through a software called RS Linx Classic. The PLC is communicating with all the machines during production and is feeding the software with all the real-time data [5].
- RS Linx: It is a software working as an intermediate between the programmable logical controller (PLC) and the Excel workbook. It receives data from PLC and exports it into an excel sheet 1/15 s [6].

The data is extracted into live Excel through the RS Linx software. This Excel contains all the real-time production data along with downtime and is saved for further processing [7].

- Digital processes: When the data is updated in the Excel file, it then goes through a python script, which is running every 1/15 s, synchronous to the speed of data being dumped to the Excel file (Fig. 4).

The Excel generated by RS Linx is further read by the python script and the following steps take place.

– Load workbook: The Excel workbook is read by Openpy XL library [8].
– Python read values: The values of the Excel are extracted into the script.
– Data stored in a variable: The value is then stored in the variables.
– Sent to IoT server: The value of the variables is then sent to the IoT server through API keys [9].
– Confirmation: Finally, a confirmation is provided that the values have been sent to the IoT platform.

- Uploaded data on server: The uploaded data on the server looks like as shown in Fig. 5. It is represented in the form of a line chart and is updated every 1/15 s (depending on internet package speed) which is sufficient for data visualization and processing. With the help of API communication, the data can be further sent to applications for further decentralization [8].
- Data sent to customized application: An application was created, where the data is sent in an organized form. The data is visible according to the production lines which are in operation. The application is updated every 1/15 s. The interface of the application can be seen in Fig. 6. The application shows production line-wise real-time data.

Fig. 5 Downtime data on the server

Fig. 6 Application interface

- Predictive maintenance: It is the maintenance during operations to reduce the failures by monitoring the performance and condition of the equipment. It is also called condition-based maintenance. With the help of real-time downtime data visualization, it is possible to predict due to which phenomena the downtime is caused frequently. Through this analysis, wear and tear data are also obtained. All this data is used to decrease the downtime and increase the efficacy throughout the plant production [10].

3.2 Steps for Energy Conservation

Energy conservation was followed by optimizing spot welding parameters. The impulse was decreased at every targeted spot which subsequently led to a lesser cycle time of the assembly. The following steps were carried out while implementing this project:

1. Spot identification
2. Optimization and improving weld parameters

- Spot identification: In this step, the spots were identified by targeting one single assembly. An Excel file was created targeting the spots which were recorded way bigger in diameter at the time of tear down.

  Metal thickness is the parameter that influences weld quality. As seen in Fig. 7, a spot weld is defined between three different layers of metals having different widths. In this weld, the spot is within the boundaries of the width and blends the three layers accurately. This defines a proper weld spot.
- Optimization and improving welding parameters: Below is the screenshot of the Bosch 6000 software. It has all the welding data of a spot. It includes Spot ID, Program Number, and Squeeze time, Weld Time, Hold Time, and Impulse (Fig. 8).

Impulse (no unit): This indicates the repetition of the welding program function during one weld sequence, wherein some time is allotted for squeezing, welding, and holding.

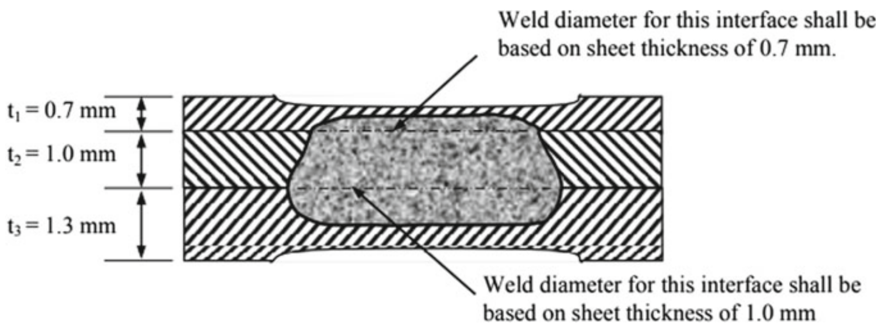

Fig. 7 Factors defining weld quality

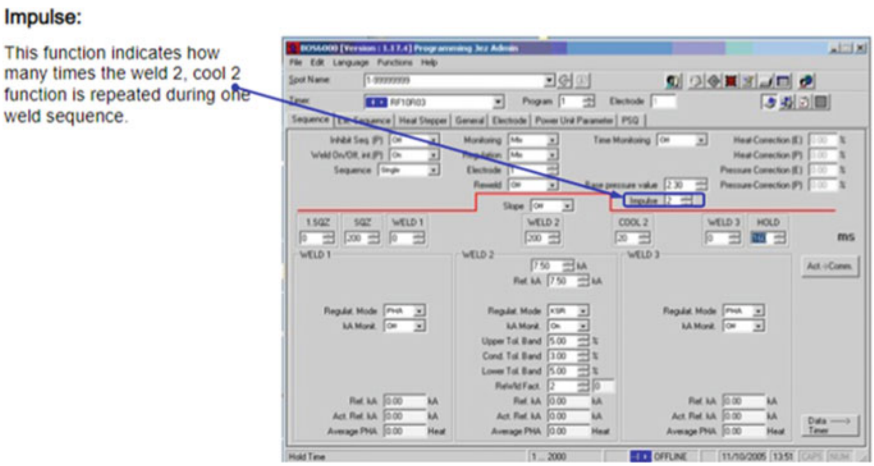

Fig. 8 BOS 6000 software screenshot [11]

Generally, the impulse for a spot varies from 4 to 6. Every spot has a distinguished program number. That program is open in BOS 6000 and from here the impulse of the spot would be decreased and the changes would be saved.

4 Observations and Calculations

Considering communication lag between various cyber-physical systems, a minimum gap of 1/15 s was observed for the most accurate data transmission. The Industry 4.0 application could provide real-time downtime data updating every 1/15 s.

4.1 Sustainable Manufacturing Observations and Calculations

During the sustainable energy project, the spots which were to be targeted were decided by the teardown data analysis. Spots exceeding the required diameters were noted and finalized for optimization (Fig. 9).

The process of optimization of welding parameters included decreasing one impulse from the current welding parameters for all the targeted spots, which was done in the weld controller software. After spot welding parameter optimization, a certain decrease in cycle time and energy consumption was observed. The calculation was done with optimization in ten spots. Assume that the total cycle time of the part was 78 s, wherein parts produced in one day were taken to be 200.

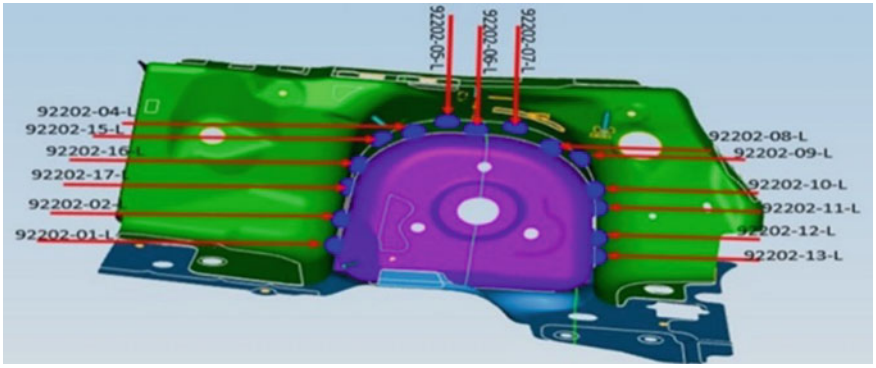

Fig. 9 Target spots for optimization as their width diameter exceeds than required

$$\text{Decrease in 1 Impulse} = 117\text{ms} = 0.117 \text{ sec, reduction in the cycle time} \tag{1}$$

$$\text{Decrease in 1 Impulse at 10 Spots} = 0.117 \text{ x } 10 = 1.17 \text{ sec saved in 1 part} \tag{2}$$

$$\text{Assuming After Production of 10 Parts} = 780 \text{ sec} \tag{3}$$

$$\text{Time saved} = 1.17 \text{ x } 10 = 11.7 \text{ sec} \tag{4}$$

$$\text{Producing parts in a day} = 200 \text{ pts}, 200/10 = 20 \tag{5}$$

$$\text{Time saved in 1 day} = 1.17 \text{ x } 200 = 234 \text{ sec} \tag{6}$$

$$\text{Extra Parts Made in 1 day after optimization} = 234/78 = 3 \text{ Parts} \tag{7}$$

$$\text{Extra Parts Made in 1 month (20 PD) after optimization} = 3 \text{ x } 20 = 60 \text{ Parts} \tag{8}$$

4.2 Resistance and Energy Calculation

The main factor that comes into play for energy conservation is resistance. During spot welding multiple factors add to resistance, taking into consideration contact resistance, which plays a major role in the impedance of spot welding [5].

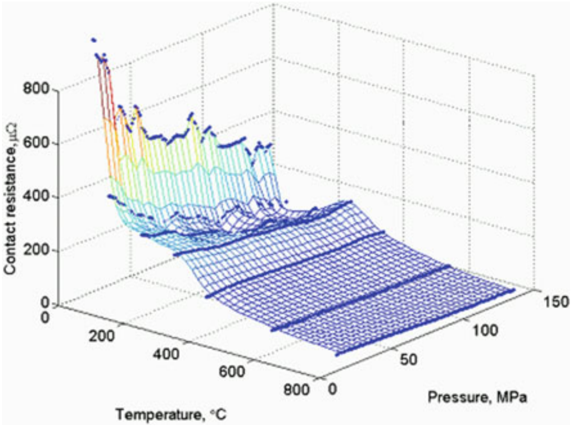

Fig. 10 Resistance chart for spot welding [13]

Contact resistance is dynamic in nature and is dependent on temperature and pressure as seen in Fig. 10. For calculation we take an assumption of $4.7 \times 10^{-5}\ \Omega$ as resistance for energy conservation because resistance starts decreasing from that particular point with an increase in temperature, as can be seen in Fig. 10 [12].

Power consumption can be calculated by Ohm's law of energy:

$$Q = I^2RT,\ I = \text{Current (Amp)},\ T = \text{time (sec)},\ R = \text{Resistance (ohm)} \quad (9)$$

$$R = \rho * L/AL = \text{Length of the cross section},\ A = \text{Area of cross section} \quad (10)$$

$$\rho \text{ for metal } = 20 * 10^{-8}\Omega.\text{ m} \quad (11)$$

$$\text{Length is the width of the material which is welded } = 3\text{mm } = 3 * 10^{-3} \quad (12)$$

$$\text{Area of the circular cross section} = (\pi/4) \times \text{D2} = 3.14 * 4 * 10^{-6} mm^2 \quad (13)$$

$$\text{Resistance } = 4.7 * 10^{-5}\Omega \quad (14)$$

$$\text{Energy } = I^2RT = \left(7 * 10^3\right)^2 * (4.7 \text{ x } 10 - 5) * (0.117) = 270\text{ J } = 1 \text{ Impulse} \quad (15)$$

$$\text{Energy Saved } = 10 \text{ Impulses (by decreasing 10 impulses in 1 part)} \quad (16)$$

$$\text{Total Energy saved } = 10 * 270 = 2700 \text{ Joule in 1 part} \quad (17)$$

$$\text{Energy Saved in 1 day} = 203 * 2700 = 225720\ \text{J} = 225.7\ \text{kJ} \tag{18}$$

$$\text{Energy Saved in 1 Month(20PD)} = 225.7 * 20 = 4514\ \text{kJ} \tag{19}$$

$$1\text{kJ} = 0.27\text{Watt Hour, so } 4514\ \text{kJ} = 1.25\ \text{Kilowatt Hour} = 1.25\ \text{Unit of electricity} \tag{20}$$

5 Conclusion

Implementation of Industry 4.0 and sustainable manufacturing has been a step toward the smart factory, thus increasing the efficacy throughout the plant, be it better production rates, less downtime, or better energy consumption. The projects have come out to be a successful way of moving toward digital manufacturing [14, 15] (Fig. 11).

Through the implementation of Industry 4.0, the downtime data is accessible globally which is updated every 1/15 s. The process of data collection includes no human intervention, making it less prone to errors and ensuring greater precision and accuracy. The data is now used for sampling preventive maintenance and is visible in a graphical form for better data analysis [15].

After implementing sustainable manufacturing, assembly production increased by 5%. The parts produced in one day were 209, and parts produced in one month were 1080. Energy saved in one year would be equivalent to 15 units of electricity (54,168 kJ) for one part where 10 spots are optimized. In a welding atmosphere, there are numerous parts being manufactured with an average of 50 spots in every part. If the number of parts taken into consideration is increased by 10 and all the spots in the part are optimized, energy saved could be equivalent to 1800 units of electricity per

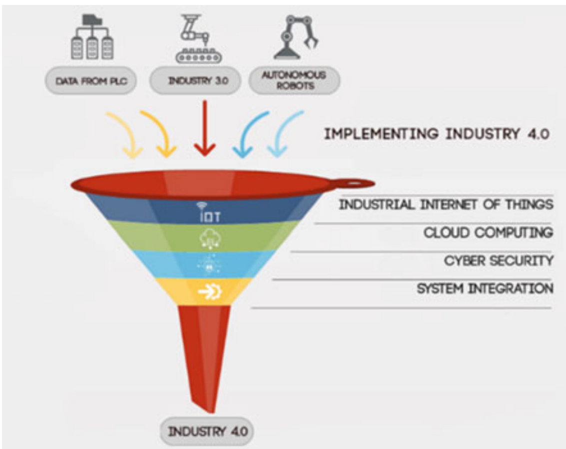

Fig. 11 Industry 4.0 summary infographic

year. Energy consumption is a function of time and will be continuously improved and monitored.

$$\text{Energy saved after optimizing 50 spots in 1 part } = 270 * 50 = 13,500\text{ J} \quad (21)$$

$$\text{Energy Saved in 1 day for 1 part } = 203 * 13500 = 27,40,500\text{ J } = 2740.5\text{ kJ} \quad (22)$$

$$\text{Energy Saved in 1 Month (20PD) for 1 part } = 2740.5 * 20 = 54810\text{ kJ} \quad (23)$$

$$54810\text{ kJ } = 15.225\text{Kilowatt Hour } = \text{ 15 units of electricity saved for 1 part} \quad (24)$$

$$\text{Energy saved for 1 part in 1 year } = 15 * 12 = 180\text{ units} \quad (25)$$

$$\text{Energy saved for 10 parts in 1 year } = 1800\text{ units} \quad (26)$$

6 Future Prospectus

Implementing Industry 4.0 leaves a scope of innovation and advancements across all operations. It sets a background toward customization and additive manufacturing. Industry 5.0 is the future fifth industrial revolution. It is going to be beyond manufacturing commodities and essentials for obtaining profits. It will shift the aim to contribute toward the betterment of society. Upskill of the operators would be done to teach and communicate with machines.

New opportunities for personalized production would be developed once the machines start to recognize and optimize repeatable processes with the help of Industry 4.0 because personalization is the future.

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