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Amaresh Chakrabarti
Manish Arora *Editors*

Industry 4.0 and Advanced Manufacturing

Proceedings of I-4AM 2019

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ISSN 2195-4356 ISSN 2195-4364 (electronic)
Lecture Notes in Mechanical Engineering
ISBN 978-981-15-5688-3 ISBN 978-981-15-5689-0 (eBook)
https://doi.org/10.1007/978-981-15-5689-0

This Springer imprint is published by the registered company Springer Nature Singapore Pte Ltd.
The registered company address is: 152 Beach Road, #21-01/04 Gateway East, Singapore 189721, Singapore

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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 First International Conference on *Industry 4.0 and Advanced Manufacturing* (I-4AM 19) held at the National Science Seminar Complex, Indian Institute of Science, Bangalore, India, during 28–29 June 2019. I-4AM 19 is the first 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 19 was hosted 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 19 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.

Forty-four abstracts were submitted to I-4AM 19, from which 40 were accepted for submission as full papers. Thirty-nine full papers were submitted, which were reviewed by experts from the I-4AM 19 International Programme Committee comprising 34 members from over 20 institutions, industries or organisations. Finally, 28 full papers, authored by 76 researchers (76 unique authors) from 40 institutions, industries or organisations from 3 countries and from 3 continents, were selected for presentation at the conference and for publication as chapters in this book.

I-4AM 19 had 28 papers with podium presentations followed by discussion. It had six academic keynotes from prominent researchers and practitioners from around the world such as Mike Gregory from University of Cambridge, UK; Niels Lohse, from

Loughborough University, UK; Rudra Pratap from Indian Institute of Science, Bangalore, India; Suhas Joshi from Indian Institute of Technology, Bombay, India; Ramesh Babu N. from Indian Institute of Technology, Madras, India; and Suresh Palanisamy, from Swinburne University, Australia. It had five Industrial keynotes from prominent industry and organisations around India such as Debashish Bhattacharjee from Tata Steel, India; Thanga Jawahar from Tata Consultancy Services, India; Purnendu Sinha from the Tata Group, Bengaluru, India; Chandrashekar Bharathi from AceMicromatic MIT, India; and Vidyabhushana Hande from Siemens Technology, India.

It had five panel discussions: "Policy Challenges and Opportunities in Industry 4.0 and Advanced Manufacturing"; "Challenges and Opportunities for Industry in Industry 4.0 and Advanced Manufacturing"; "Challenges and Opportunities in Precision Manufacturing for the Strategic Sector"; "Challenges and Opportunities for Training and Research in Advanced Manufacturing and Industry 4.0"; and "Challenges and Opportunities for Start-ups in Advanced Manufacturing and Industry 4.0". Over 40 thought leaders from industry, academia and policy sectors participated in the panel discussions. Ten start-ups were invited to join I-4AM 19 free of cost; were given stalls to display their products; and special sessions were organised in which they could interact with successful entrepreneurs who advised them on entrepreneurship.

Bengaluru, India

Amaresh Chakrabarti
Manish Arora

About This book

This book, *Industry 4.0 and Advanced Manufacturing—Proceedings of I-4AM 2019*, focuses on the following topics:

- Materials Processing and Joining;
- Controls, Autonomous Systems, and Robotics;
- Policy and Entrepreneurship;
- Supply Chains and Industry 4.0;
- Digital Manufacturing; and
- 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 19, 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 partners: (Confederation of Indian Industry (CII), Fraunhofer and VDMA); the major sponsors (UK Science and Innovation Network 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 19. 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 premises to be used for the various functions in 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. Ranjan B. S. C., Mr. Kiran Ghadge, Mr. Puneeth

K. S., Mr. Ishaan Kaushal, Mr. Apoorv Bhatt, Mr. Anubhab Majumdar, Mr. Paridhi S. and Mr. Dhiraj Kumar 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 in the organisation of the conference. Finally, we thank Springer, especially its Editor Ms. Swati Meherishi and its editorial support team, for their wonderful support.

Bengaluru, India

Amaresh Chakrabarti
Manish Arora

About the Conference

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. This conference intended to provide a platform to bring together all stakeholders in manufacturing and Industry 4.0, in particular those in academia, industry and policy in both India and abroad, for them to deliberate on the nature, needs, challenges, opportunities, problems and solutions in this transformational area of endeavour. A specific focus of this conference has been to provide a platform for exploring avenues for creating a vision of, and enablers for sustainable, affordable and human-centric Industry 4.0 and for showcasing cutting edge practice, research and educational innovation in this crucial and rapidly evolving area.

I-4AM 19 (pronounced i-forum 2019) included keynotes, panel discussions and mentoring sessions from thought leaders in industry, academia, strategic sectors and policy bodies, as well as presentation sessions for research papers. All research papers submitted had undergone peer review process by the International Programme Committee; selected papers have been published in a proceedings book published by Springer.

I-4AM 19 was organised by the Centre for Product Design and Manufacturing, Indian Institute of Science, under its CEFC on I4.0India@IISc (Smart Factory) within the SAMARTH Udyog Bharat 4.0 programme of the Department of Heavy Industries, Government of India.

The conference contained:

- Keynote presentations from eminent experts from industry, academia, policy and strategic sectors;
- Panel discussions by thought leaders from major stakeholders in advanced manufacturing and industry 4.0;
- Presentations of peer-reviewed papers as podium presentations;
- Mentoring sessions for start-ups;
- Display of innovations from start-ups in industrial stalls.

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Digital Manufacturing

Materials Processing and Joining

About the Editors

Amaresh Chakrabarti is a Senior Professor and current Chairman for the Centre for Product Design & Manufacturing, Indian Institute of Science (IISc), Bangalore, India. He received his B.E. in Mechanical Engineering from IIEST Shibpur India, M.E. in Mechanical Systems Design from IISc Bangalore, and Ph.D. in Engineering Design from the University of Cambridge, UK. His research interests are in synthesis, creativity, sustainability, informatics, research methodology and Industry 4.0. He has published 18 books, over 300 peer-reviewed articles, and is the series editor for Springer's book series on Design Science & Innovation. He has been granted/pending for 10 patent applications. He serves on the editorial boards of numerous prestigious journals and has been on the Advisory and Management Board of the Design Society; member of the CII National Committee on Design India; Jury for the India Design Mark; and invitee to the CII Smart Manufacturing Council India. He is an Honorary Fellow of the Institution of Engineering Designers, the peer society under the UK Royal Charter in engineering design, and TUM Ambassador Awardee from TU Munich Germany.

Manish Arora is Assistant Professor at the Centre for Product Design and Manufacturing, Indian Institute of Science, Bengaluru. He obtained his Ph.D. in Applied Physics from the University of Twente, The Netherlands (2006) and B.Tech. in Chemical Engineering from Indian Institute of Technology, Delhi (2002). He has 70+ patent and research publications both in national and international level to his credit. His areas of interest include biomedical devices, co-design, collaboration, open-source in design and quality manufacturing of medical devices. He is the Principal Investigator in UTSAAH Lab, which aims at developing affordable and accessible medical technology solutions for promoting universal healthcare. He teaches courses at IISc on Mechatronics and Design of Biomedical Devices and Systems.

Industry 4.0

Industry 4.0-Connected Drives Using OPC UA

Andrew Kirubsingh Philip Samuel, A. Shyamkumar, and H. Ramesh

Abstract The field of industrial automation has undergone exponential growth in the past century. The various industrial revolutions have impacted industrial automation to a great extent. Industrial Products such as controllers, drivers, and field devices have undergone various changes to meet user demands. Of these demands, features such as interoperability, reduced cycle time, increased productivity, and security stand out. This paper deals with interoperability issues with different vendor controllers and softwares for accessing data. It also describes the concept of accessing servo drive parameters such as position, velocity, acceleration, deceleration, etc. from different motion controllers through third-party software such as MS-Excel using the OPC UA protocol. To validate our software architecture, we have built an *XY* axes plotter system, which has the ability to draw a 2D sketch. This simplified architecture is used to demonstrate the industry 4.0 based OPC UA concept for the educational community.

Keywords OPC UA-OPC unified architecture · PLC-programmable logic controller · PLCopen · Sercos-serial real-time communication system · MLC-motion logic controller

1 Introduction

Industrial automation involves the use of control systems, such as computers and information technologies for handling different processes and machineries in an industry. Motion control is a sub-field of automation, consisting of the systems

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A. Chakrabarti and M. Arora (eds.), *Industry 4.0 and Advanced Manufacturing*, Lecture Notes in Mechanical Engineering,
https://doi.org/10.1007/978-981-15-5689-0_1

involved in moving parts of machines in a controlled manner. The basic architecture of a motion control system consists of five main components which are listed as follows:

1. A controller to generate the control signals.
2. A driver to transform the control signal from the motion controller into energy that is presented to the actuator.
3. A prime mover or actuator such as a hydraulic pump, pneumatic cylinder, linear actuator, or electric motor for output motion.
4. Feedback sensors such as absolute and incremental encoders, Hall effect devices to return the position or velocity of the actuator to the motion controller.
5. Mechanical components to transform the motion of the actuator into the desired motion, including gears, ball screws, belts, and linear and rotational bearings.

The disadvantages of a conventional motion control system used in a typical industry include increased latency, increased complexity, higher cost, and requires highly skilled operators [1]. Existing communication protocols such as TCP/IP, UDP are relatively slow in comparison with OPC UA [2]. This latency issue has been addressed in Sect. 5 of this paper. In order to overcome these issues, OPC UA enabled motion control systems can be implemented [3]. The advantages of OPC UA enabled motion control systems include enhanced interoperability, reduced cycle time, increased security, reliability, and productivity. These systems pave the way for collaborative activities between multi-vendor industrial field devices.

2 Overview of OPC UA

OPC Unified Architecture (OPC UA) is a machine to a machine communication protocol for industrial automation developed by the OPC Foundation [4]. Given the wide array of available hardware platforms and operating systems in the industry, platform independence is essential. The OPC UA Protocol widely improves the interoperability between multi-vendor field devices [4]. An OPC Server will respond to requests, and provide data to one or more OPC Clients in a standard and in a consistent manner. In order to improve openness in automation, manufacturers are embedding OPC server into the various industrial devices such as motion controllers. The OPC client is a software program that makes requests to the OPC server and acts as a bridge between the user and the OPC server [2].

Communication between the OPC client and server is realized by using the communication stacks present in the client and the server [5]. Communication stacks typically consist of features for transportation, encoding, and decoding data (see Fig. 1). The transportation protocols such as TCP send the data to the network from the client/server, thus accomplishing client/server communication. For the communication between the PLC master device and the slave device, we have used the Sercos communication protocol. Sercos III is the third generation of the Sercos interface, which is a globally standard open digital interface for the communication

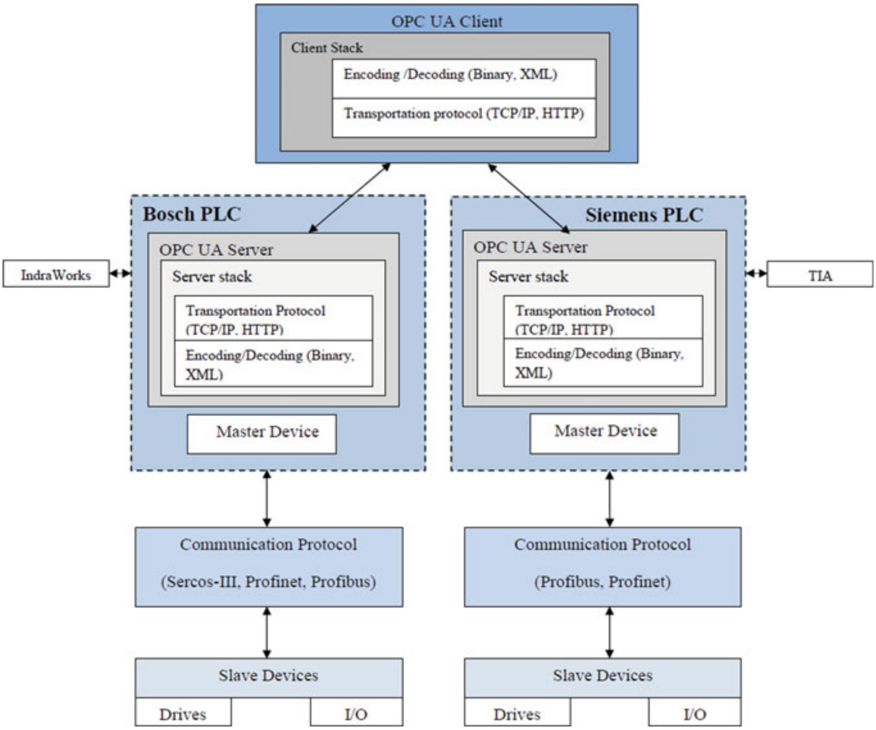


Fig. 1 Communication between the OPC server and client in multi vendors PLCs

between industrial controls, motion devices, and the like [6]. Figure 1 describes the relationship between the OPC server and the OPC client.

3 Overview of PLCopen Motion Control

PLCopen is an independent worldwide organization providing efficiency in industrial automation based on the needs of the users [7]. Today's technical challenges in the industrial control market are constantly changing, and PLCopen follows the demands of the market by defining general standards. Based on application requirements and project specifications engineers are required to use or select a wide range of motion control hardware. In the past, this required unique software to be created for each application even though the functions are the same. PLCopen motion standard provides a way to have standard application libraries that are reusable for multiple hardware platforms. This lowers development, maintenance, and support costs while eliminating confusion. In addition, engineering becomes easier, training costs decrease, and the software is reusable across platforms. This enables the industries to focus on their core competencies. Effectively, this standardization is done by defining libraries of reusable components. In this way the programming is less hardware dependent, the reusability of the application software is increased [8]. Some of the function blocks as defined in parts 1 and 2 of PLCopen include MC_MoveAbsolute, MC_MoveRelative, MC_Power, MC_Stop, etc. We have implemented these blocks to build our program.

4 Software Implementation

The software implementation is designed to do the following process. A 2D sketch is drawn in the AB viewer software. This sketch is converted to a corresponding G code file. The *XY* coordinates are extracted from the G code file. An excel file is configured as the OPC client by using the OPC expert software. The *XY* coordinates from the AB viewer software (drive parameters) are given into the excel file. This excel file containing the drive parameters feeds this data to the OPC UA server which is present in the PLC. The variables in the ladder logic of the PLC receive the parameters from the OPC server. This action is finally reflected in the motion of the motor, which is connected to the drive. Figure 2 represents the flowchart of the whole process.

The steps involved in the software implementation are explained in the following subheadings.

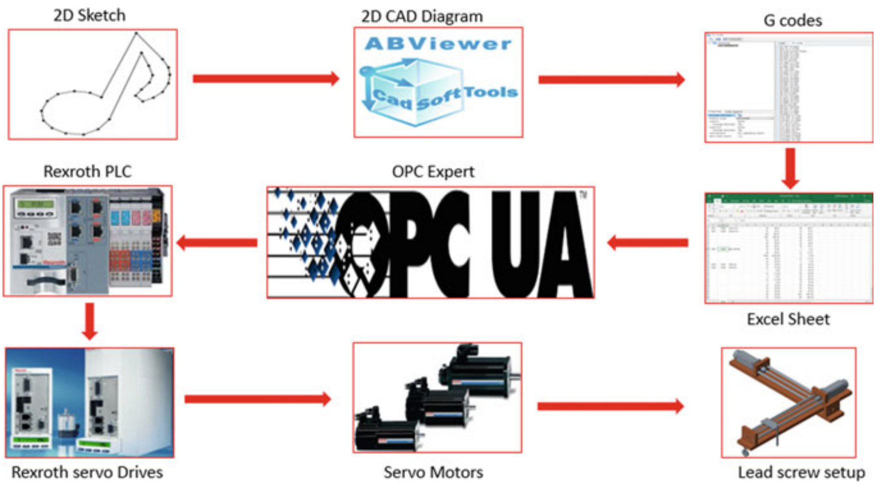


Fig. 2 Flowchart of the overall process

4.1 2D Sketch to G Codes

First of all, a 2D sketch is to be drawn in a CAD software. This sketch can be any random figure representing any object. This sketch is drawn in a software known as AB Viewer. This software has the ability to convert the drawn sketch into a G code. G code is the common name for the most widely used numerical control (NC) programming language. It is used mainly in computer-aided manufacturing to control automated machine tools [9]. The G codes consist of many instructions to be conveyed to the machine. Of these instructions, the major constituents are the *XY* coordinates. Theses *XY* coordinates of the sketch are extracted and fed into a Microsoft Excel file.

4.2 Programming of Motion Controller Using PLCopen

The main objective of the program is to manipulate the motion of the servo drives The Indraworks software is a programming software developed by Bosch Rexroth. It is a software used to program Bosch PLCs and MLCs [10]. We used a Bosch Rexroth MLC 65 controller in our project. To implement MLC in the program, the PLCopen motion library has to be included. The required function blocks of the PLCopen motion library are inserted in the ladder's rung. Figure 3 represents the sequence of operation of the program:

First, the drives are powered on. After doing so, the homing sequence is done. This is done to set a reference point to the drives. On completion of the homing operation, the variables in the PLCopen function blocks receive coordinate values from the

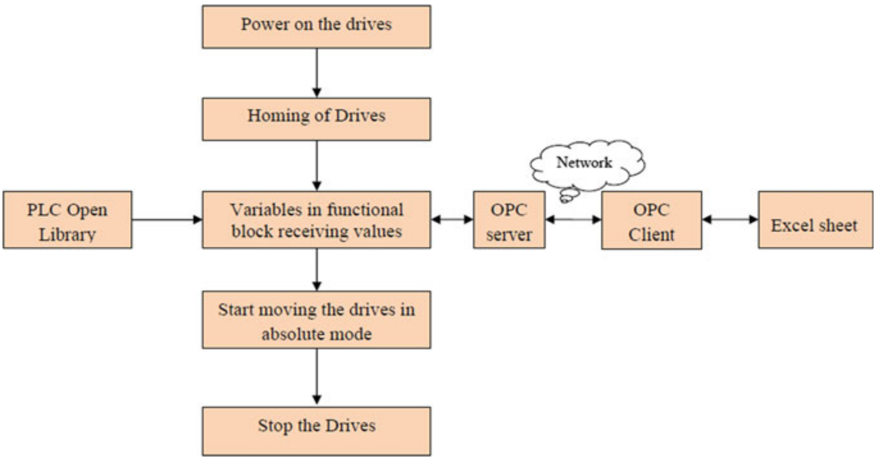


Fig. 3 Sequence of program execution

Alarms & Events | Bridged Items

Computer	OPC Server	Item ID	Item	Value	TimeStamp	Quality
172.17.2...	IndraControl OPC UA Server (opc.tcp://172....	ns=2;s=Application.Plc...	start_moving	True	11:36:13 AM	Good (192)
172.17.2...	IndraControl OPC UA Server (opc.tcp://172....	ns=2;s=Application.Plc...	stop_D1	False	11:29:57 AM	Good (192)
172.17.2...	IndraControl OPC UA Server (opc.tcp://172....	ns=2;s=Application.Plc...	stop_D2	False	11:29:57 AM	Good (192)
172.17.2...	IndraControl OPC UA Server (opc.tcp://172....	ns=2;s=Application.Plc...	home	null	1:55:28 PM	Good (192)
172.17.2...	IndraControl OPC UA Server (opc.tcp://172....	ns=2;s=Application.Plc...	power_on_1	True	11:36:15 AM	Good (192)
172.17.2...	IndraControl OPC UA Server (opc.tcp://172....	ns=2;s=Application.Plc...	power_on_2	True	11:36:14 AM	Good (192)
172.17.2...	IndraControl OPC UA Server (opc.tcp://172....	ns=2;s=Application.Plc...	Y19	70	11:37:24 AM	Good (192)
172.17.2...	IndraControl OPC UA Server (opc.tcp://172....	ns=2;s=Application.Plc...	Y18	60	11:37:24 AM	Good (192)
172.17.2...	IndraControl OPC UA Server (opc.tcp://172....	ns=2;s=Application.Plc...	Y17	50	11:37:24 AM	Good (192)
172.17.2...	IndraControl OPC UA Server (opc.tcp://172....	ns=2;s=Application.Plc...	Y2	70	11:37:24 AM	Good (192)
172.17.2...	IndraControl OPC UA Server (opc.tcp://172....	ns=2;s=Application.Plc...	Y22	95	11:37:24 AM	Good (192)
172.17.2...	IndraControl OPC UA Server (opc.tcp://172....	ns=2;s=Application.Plc...	Y21	90	11:37:24 AM	Good (192)
172.17.2...	IndraControl OPC UA Server (opc.tcp://172....	ns=2;s=Application.Plc...	Y20	80	11:38:32 AM	Good (192)
172.17.2...	IndraControl OPC UA Server (opc.tcp://172....	ns=2;s=Application.Plc...	Y12	5	11:37:24 AM	Good (192)
172.17.2...	IndraControl OPC UA Server (opc.tcp://172....	ns=2;s=Application.Plc...	Y11	1.1	11:37:24 AM	Good (192)
172.17.2...	IndraControl OPC UA Server (opc.tcp://172....	ns=2;s=Application.Plc...	Y10	0	11:37:24 AM	Good (192)

Fig. 4 OPC client software displaying the data items

excel file via the OPC protocol (See Fig. 3). On receiving the values, the drives start to move in the absolute mode that is, with respect to the reference position. After the required motion is completed, the drives are stopped.

4.3 OPC Expert

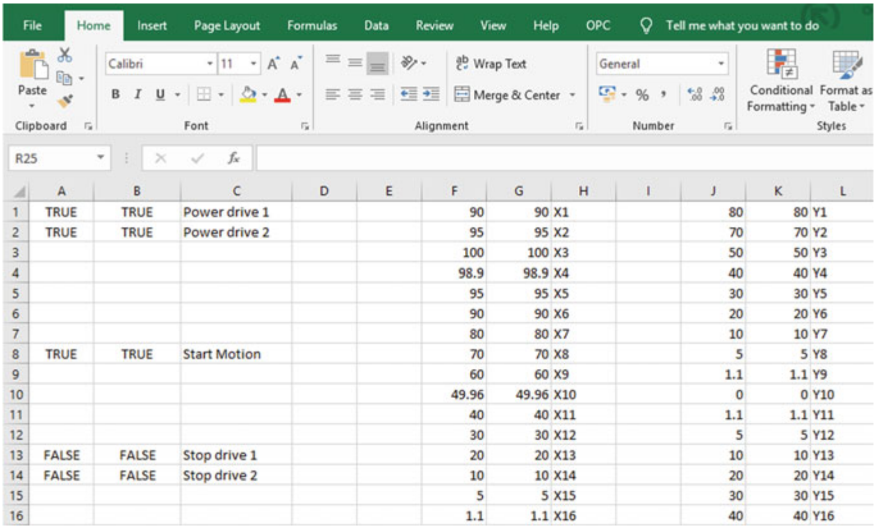
OPC Expert is a software application enabling automation personnel to easily view and manipulate OPC information. The OPC expert in our case acts as the OPC UA client. It has the ability to read and write real-time data to a specified controller. It also has the capability to configure an excel file as a sub-client [11]. After the connection is established, the items (variables) configured in the ladder logic can be viewed in the OPC client. Fields such as status of connection, item, item's value, quality of data, update rate, and data type can also be viewed in the client interface (Fig. 4). The following is the screenshot of the interface of OPC experts.

4.4 Configuring Excel as a Client

The items which are present in the OPC network (as shown in Fig. 4), can be dragged and dropped into an excel file. After the item is dropped into a cell of excel, the formula bar of that corresponding cell takes the entry '=RTD("expertrtd", "172.17.24.223", "opc.tcp://172.17.24.223:4840", "ns = 2;s = Application.PlcProg.power_on_1", 1000,B1)'.

Where

- RTD stands for Real-Time Data
- 172.17.24.223 is the IP of the controller



	A	B	C	D	E	F	G	H	I	J	K	L
1	TRUE	TRUE	Power drive 1			90	90	X1		80	80	Y1
2	TRUE	TRUE	Power drive 2			95	95	X2		70	70	Y2
3						100	100	X3		50	50	Y3
4						98.9	98.9	X4		40	40	Y4
5						95	95	X5		30	30	Y5
6						90	90	X6		20	20	Y6
7						80	80	X7		10	10	Y7
8	TRUE	TRUE	Start Motion			70	70	X8		5	5	Y8
9						60	60	X9		1.1	1.1	Y9
10						49.96	49.96	X10		0	0	Y10
11						40	40	X11		1.1	1.1	Y11
12						30	30	X12		5	5	Y12
13	FALSE	FALSE	Stop drive 1			20	20	X13		10	10	Y13
14	FALSE	FALSE	Stop drive 2			10	10	X14		20	20	Y14
15						5	5	X15		30	30	Y15
16						1.1	1.1	X16		40	40	Y16

Fig. 5 OPC linked Microsoft excel displaying the variables

- Application.PlcProg.power_on_1 is the Item whose value can be manipulated
- B1 is the neighbor cell, which linked to the cell containing the OPC data (cell A1).

This OPC data cell transfers the changed value to the OPC server [11]. The following is the screenshot of the OPC linked excel file (Fig. 5).

5 Network Analysis

The response time in conventional motion control systems is normally very high [2]. By incorporating the OPC UA protocol, this response time in motion control systems is drastically reduced. For the purpose of analyzing the communication between the OPC server and the client, we have used Wireshark. Wireshark is a free and open-source packet analyzer [12]. It is used for network troubleshooting, software, and communications protocol analysis.

The following inferences were obtained from wire shark:

1. The poll response time between the write request (made by the Computer) and the write response (given by the controller) was found to be in the range of 0.5–0.9 ms (Fig. 6).
2. The evidence for the transfer of the data packets (parameters) to the variables via the OPC network was verified.

Fig. 6 Wireshark displaying the network parameters

The following is the screenshot of the Wireshark software:

Since the poll response time is very low, communication lag in motion controllers can be eliminated.

6 Hardware Implementation

In order to validate the above software architecture, we built an *XY* plotter system [13]. In this setup there are two axes mounted perpendicular to each other (Fig. 7). Each axis has a servo motor for its actuation. A threaded shaft is coupled to the motor's shaft by using a coupler [9]. A nut traverses along the threaded shaft so as to convert the rotary motion of the motor to linear motion. Side rails are mounted parallel to the threaded shaft on both sides and they act as guideways. A moving plate is fixed to each of the axis' nut. A sketcher is attached to this moving plate. This sketcher finally draws the required 2D sketch by using the converted motion from the motor (rotary to linear). The following is the CAD design of the *XY* plotter.

Whenever the servo motors receive command from the driver to move, its shaft rotates. Since this shaft is coupled to the threaded shaft, the rotary motion is converted to linear motion of the nut and thus the moving plates. A blank paper is kept in the workspace of the *XY* plotter. The attached sketcher, mounted onto the *Y* axis, draws the required figure in the paper. The following image is the photograph of the actual assembled *XY* plotter along with the other components (Fig. 8).

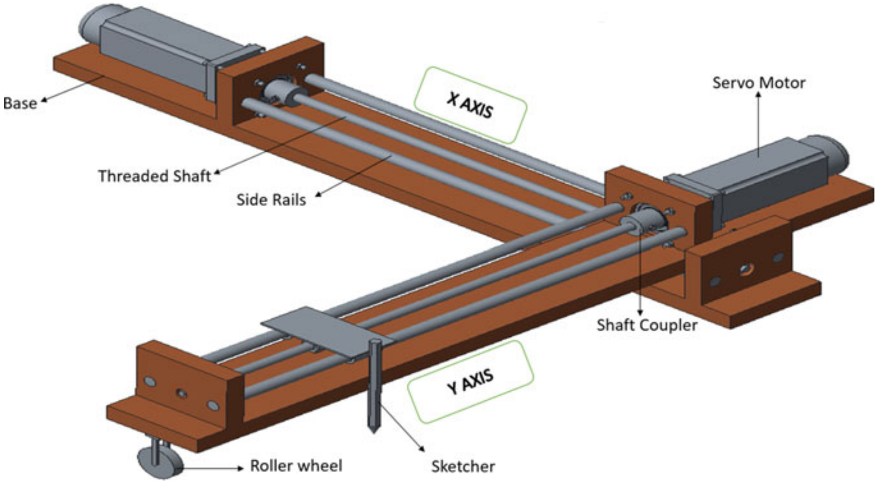


Fig. 7 CAD diagram of the *XY* plotter system

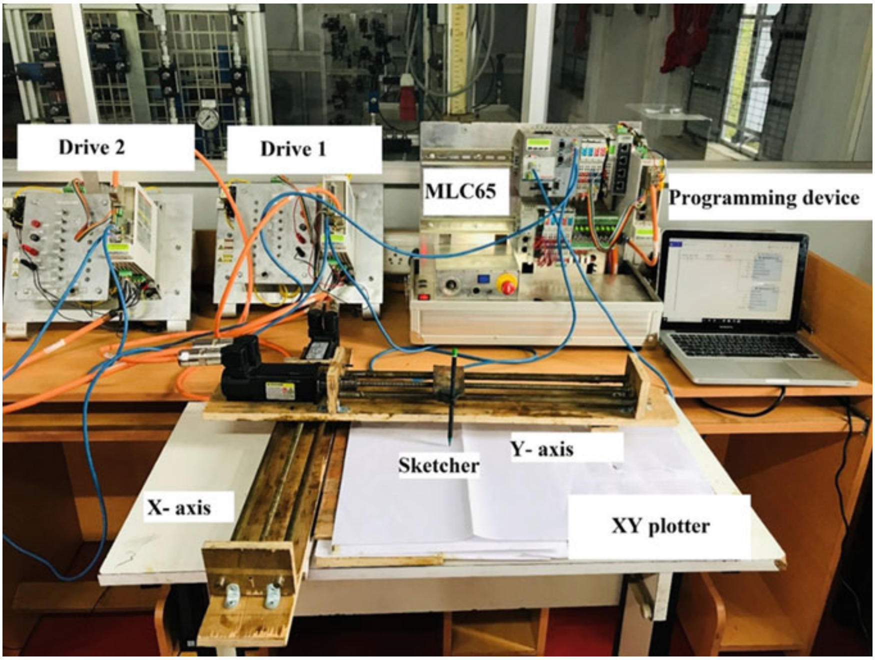


Fig. 8 Snapshot of the *XY* plotter with other components of the system

7 Conclusions and Future Work

Conventionally, Bosch PLC or Siemens PLC can be controlled by their own proprietary software, but by using our software architecture we can control multi-brands PLCs. By using the OPC UA protocol, the response time was drastically reduced (to the order of 0.5–0.9 ms). Hence, the problem of communication lag in motion control systems can be eliminated completely by the above architecture. Since interoperability has been achieved, the productivity of the various industrial field devices is widely improved. As discussed, the Industry 4.0 systems in industries are very complex for students to understand. Hence, this paper simplifies the complexity by providing a simple demonstration. This helps the students to have a better understanding of Industry 4.0 based upon OPC UA. The mentioned architecture can be implemented as an educational tool for laboratory demonstrations of Industry 4.0 systems.

As a part of future work, the proprietary OPC client software may be replaced with an open-source version. The number of axes can be extended to three from two (X, Y, Z). Instead of a sketcher, a driller or a laser cutter can be mounted. This can act as an industrial application for machining operations.

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Conceptual Framework to Assess the Maturity and Readiness Towards Industry 4.0

Pinosh Kumar Hajoary and K. B. Akhilesh

Abstract The paper provides a comprehensive framework to assess, i.e. serves as the diagnostic tool to assess the current capabilities of an organization. First, to provide a prescriptive purpose in order to identify future desirable levels and provide holistic improvement guidelines for the organization in terms of maturity and readiness of a manufacturing organization. Second, to discuss the current status and policies of India towards Industry 4.0. To successfully transform Indian Manufacturing industry towards Industry 4.0, it is necessary to clearly define strategies, standard technological policies taking all stakeholders into account to build strong technological standard roadmap with a strong economic and social system that can quickly respond to any unexpected changes in the sector.

Keywords Industry 4.0 · Maturity · Readiness · Policies · Roadmap · Strategies

1 Introduction—Past, Present and Future

Industry 4.0 also termed as 'Smart Manufacturing' or otherwise called as fourth industrial revolution was first coined in Germany by German academics, practitioners and government officials during Hannover Fair in the year 2011. The term smart manufacturing is used interchangeably with Industry 4.0 and Smart factory. Some of them call it as 'Industrial Internet of Things'. According to Gilchrist [1] the Fourth Industrial/Industry 4.0 is defined with respect to design principles and its technological trends. However, the term 'Fourth Industrial Revolution' has been widely used in most countries to define the next-generation technological transformation in the manufacturing industry. Smart manufacturing or the fourth industrial revolution is a subclass of digital transformation in already prevailing business settings [2]. The

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A. Chakrabarti and M. Arora (eds.), *Industry 4.0 and Advanced Manufacturing*, Lecture Notes in Mechanical Engineering,
https://doi.org/10.1007/978-981-15-5689-0_2

Industry 4.0 will have an impact on the social, technological, political and economic status of the country. Earlier the first industrial revolution was based on normal mechanization of the production process using water powered by steam power. Later Electricity was introduced instead of water and steam power which lead to the introduction of assembly line led mass production system in manufacturing. The Third Industrial Revolution is mostly concerned with the extensive use of electronics and communication along with IT (Information Technology) to further automate the system. With digital automation and series of advancement in information technology, Fourth Industrial Revolution which we are currently talking about came into being with the introduction of cyber-physical system network in the entire manufacture process via dedicated platform thus permitting real-time data distribution within the network and enabling interactions between machine to machine (M2M) and machine to human (M2H) with accurate speed and precision. Further, this has given rise to an integrated connection with the physical systems in the network enabling decentralized decision-making and high level of automation in the process. Smart manufacturing is the convergence and fusion of groundbreaking digital technologies that are expected to change the dimensions of the manufacturing sector beyond imagination given the fact that huge data volumes are generated by the system day by day. The volume of data generated is stored in the remote cloud-enabling access to any part of the world. The emergence of virtual technology merged with physical things resulted in creation of cyber-physical systems resulting in a new industrial concept called 'Smart Factory'. In many countries including India, Germany, China and the U.S., the term fourth industrial revolution is widely used as it is more familiar to earlier versions of revolutions. However, in this study, Industry 4.0 will be interchangeably used as smart manufacturing and smart factory. Manufacturing sector constitutes one of the strongest growing sectors in India with 16–17% contribution to its GDP. By the end of 2025, it is expected to touch 25% and create 90 million new jobs [3]. As per the report from India Brand Equity Foundation [4], India is likely to reach 1 trillion US Dollars by the year 2025 and is expected to become the top three growth economic nations in the world. India is currently at 30th on World Economic Forum global manufacturing index 2017–18.

2 Literature Review

Despite growing research on the economic benefits of Industry 4.0, very little attention is paid to assess the maturity and readiness of organizations in moving towards Industry 4.0. Maturity assessment has proved to be a necessary part of the organization to assess and evaluate the current state of its capability [5]. A lot of studies earlier concentrated on the IT maturity model (CMMI), IT Balanced Scorecard Maturity Model, Knowledge Management Maturity Model [6]. On the other hand, in the ever-changing business environment and technological changes, it has become a necessity for organizations to undertake constant upgradation and improvement. Identification of present system practices and technology have become extremely important to move forward in ever-changing environment. Maturity model consists of step by step chronological stage that assesses the level of organization on selected dimensions. This model helps to reveal the current stage and desirable future stages of readiness and maturity of the organization. Quite a few assessment tools have been developed earlier both by academia and practitioners with the main aim of providing holistic frameworks for assessing the readiness and to analyze their status quo by a dedicated instrument within the organization. VDMA (Mechanical Engineering Industry Association of Germany) [7] has identified six dimensions of Industry 4.0 with micro and macro analysis of the readiness of the manufacturing industry. The key dimensions are (i) Strategy and organization (ii) Smart factory (iii) Smart products (iv) Data-driven services (v) Employees. However, Capgemini Consulting (2014) has devised a maturity dashboard for accessing manufacturing industry readiness towards Industry 4.0 concentrating on three main drivers namely business model, digital practices, digital capabilities. Morteza Ghobakhloo [8] in his study on the strategic roadmap for Industry4.0 has adopted eight design principles for successful implementation; they are (i) Service orientation (ii) Smart products (iii) Smart factory (iv) Interoperability (v) Modularity (vi) Virtualization (vii) System Integration and (viii) Corporate social responsibility many organizations at present are not sure about the outcomes and benefits of Industry 4.0 due to lack of understanding and knowledge [9]. Tarhan et al. [10] defined the maturity model as a logical path in several business processes. However, maturity models are a vital technique to evaluate organizations in multiple dimensions from diverse perspectives [11]. PwC has designed an online self-assessment tool with six dimensions [12]. Earlier, the Industrial Internet Maturity Model was devised to measure the maturity of the Industrial Internet in an organization [13]. However, there are a limited number of studies and none of the current models could empirically demonstrate the validity of the model and bring about a standard framework to assess the maturity and readiness of a manufacturing organization in India.

2.1 Proposed Conceptual Framework

Technology and digitalization have changed organizations over the years. Digital transformation of organizations has completely opened the new era of opportunities and challenges. Organizations today are bound to undergo internal and external sea changes [9] across all functions. Based on the literature, we have come up with eight dimensions on maturity and readiness framework to assess the manufacturing organization towards Industry 4.0 (Fig. 1).

2.1.1 Strategy and Organization

Raising the topic of Industry 4.0 or smart manufacturing raises some questions from business leaders, government and practitioners. Questions like: what does Industry

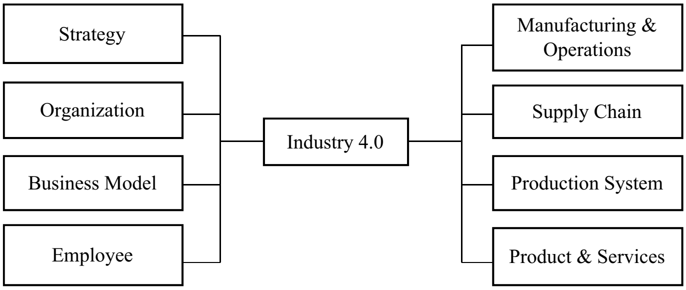

Fig. 1 Conceptual framework to assess maturity and readiness

4.0 really mean to our business and country? How it will impact the current business strategy of our organization? What are the short-term and long-term requirements, policies and opportunities? Such questions among industrial leaders and policy-makers show that the concept is recognized and some of them are on the way of embedding it into their business strategy and culture. In order to understand the current status of an organization, it is necessary to understand the degree of strategy implementation at the organizational and departmental levels. To successfully implement Industry 4.0 requires far more than the senior leadership team playing lip-service by purchasing new technology. However, it requires cross-functional teams to support and collaborate by implementing relevant measurement tools (KPI) at both a strategic and operational level. Moreover, it is also important for organizations to invest in new technologies and understand the value of it.

2.1.2 Business Model

The blurring of the difference between products and services has resulted in the proliferation of 'As a service business model'. Industry 4.0 presents enormous opportunities for organizations to redefine their current business model and are developing plans to ensure that their business model is contemporary and regularly updated. A lot of data are being generated from customers, organizations and products day by day. For example, real-time tracking of product, real-time and automated scheduling with the help of technology has enhanced the data-driven decision-making thus breaking the traditional routes to market and customer touchpoints. Such a process requires integrated marketing channels along with robust IT supported infrastructure.

2.1.3 Employee

Industry4.0 acceptance and adoption will have a far-reaching impact on the current employee's skill sets, roles and qualifications [3, 14, 15]. Another important aspect in this context is the willingness to change and accept the digital culture and concerns of data transparency, safety in workplaces. Hence, the success of the implementation of Industry 4.0 technologies in the organization will depend on the ability of the employees to learn and reskills themselves with the relevant skill sets. Most of the manual jobs will be automated and new roles will demand critical thinking ability and data analysis skills.

2.1.4 Manufacturing and Operations

Manufacturing and Operations is the heart of the vision of Industry 4.0 [16]. Its vision is to fully customize products without human intervention, i.e. autonomously produced in a self-optimizing environment. It's an environment wherein cyber and physical come together as one. An IoT-enabled machine to machine interaction takes place to optimize process that allows collection of data and is used to plan, optimize and generate meaningful information out of it. Machine to Machine (M2M) interaction that can be controlled and is upgradable, automatic material handling with self-optimizing processes, digital modelling used in prototyping and development, data storage and security along with predictive maintenance describes the characteristics of Industry 4.0.

2.1.5 Supply Chain

Industry 4.0 is not only about vertical and horizontal digitization; it is much more than digitization. However, digitization is the pre-condition towards Industry 4.0. Supply chain integration becomes a very important part of manufacturing organizations. Better supply chain agility could mean shorter lead time with shorter delivery without spending much on inventory cost. However, implementation of Industry 4.0 in supply chain could bring about better visibility and flexibility with real-time inventory control using real-time data. In such cases, supply chain lead times will be more agile and shorter. The secret of success lies in an integrated supply chain network wherein all parties are connected, and data are shared on real-time basis to its customers and suppliers.

2.1.6 Production System

Production technology has evolved over the years from craft-based production to flow line, TPS and Job Shop. Since then, Toyota has introduced new methods of production called JIT (Just in time) and lean manufacturing. In the era of cyber-physical system, Flexible manufacturing system (FMS), Manufacturing Execution System (MES) and Additive manufacturing have become a talking point for most of industries at present. In this environment, production equipment and systems are fully automated in the entire production system and at the factory level.

2.1.7 Products and Services

Over the last 20 years, there has been an increasing distinction between a physical product and a genuine service. The difference between them is slowly blurring with the advancement of technology [16]. At present, products and services are very important and both go along hand in hand [15, 17]. Products are equipped with smart sensors, RFID tags, embedded systems, GPS, etc. to track hold of quality, location and status. Earlier, products were produced with standard mass production without late differentiation. However, at present products are customized as per the needs of the customer with late differentiation. Organizations use data generated from the products for analyzing historical data to generate revenue out of it.

3 India's Current Status Towards Industry 4.0

The widespread adoption of Industry 4.0 also called Smart Manufacturing in India is still at a nascent stage. Since its inception, it has gained widespread adoption in European counties like Germany, French, the UK and the Netherlands. India can leapfrog under the lines of 'Make in India' initiative undertaken by the government to make India the powerhouse of manufacturing. Policies like 'National Policy for Advanced Manufacturing' will play a vital role in paving the way towards adopting the new technologies in the era of the fourth industrial revolution. Industry 4.0 is much more than digitization; however, digitization is the pre-condition for Industry 4.0. India has a lot of potentials to leapfrog towards Industry 4.0 because of its availability of skilled and low-cost manpower in the areas of information technology. It is said that to unleash the true potential of Industry 4.0, it has to be accessible and adopted by 50 million-plus small-scale enterprises in the country [18]. Advancement of technology in manufacturing has brought ample opportunities for the Indian manufacturing sector to adopt and adapt to changes according to current market needs. India is currently the 6th largest manufacturing country in the world and is expected to become the 5th largest by the end of 2020 as per global manufacturing index study published by Deloitte. According to the study undertaken by World Economic Forum, India is ranked at 91 in Network readiness index among 139 counties in the world. However, in terms of ICT use and government efficiency, it is currently ranked at 68. Singapore tops twice in a row in the network readiness index followed by Finland while the United States is ranked 5th (Table 1).

India is steadily moving up in terms of its technological readiness in the global competitive index 2017–18 edition. According to the International Federation of Robotics, robotics sales in India grew by 27% from the previous year to a peak of 2,627 units in the year 2017. It is currently ranked at 40th among 137 countries in the world [19]. The score has improved across most of the pillars of competitiveness particularly in the areas of higher education and training from 75th rank to 69th rank, public spending to 20th while technology readiness at 107th, Institutions at 39th,

Table 1 Global network readiness index 2016

Readiness index 2016	Position
Singapore	1
U.S.A	5
U.K	8
Japan	10
Germany	15
China	59
Sri Lanka	63
India	91
Pakistan	110

Source World Economic Forum (2016)

Table 2 Yearly global competitive index ranking of India

Year	2012–13	2013–14	2014–15	2015–16	2016–17	2017–18
India/total country	59/144	60/148	71/144	55/140	39/138	40/137
Score	4.3	4.3	4.2	4.3	4.5	4.6

Source World Economic Forum (2018)

Infrastructure at 66th, Microeconomic environment at 80th but corruption remains the biggest worry factor for doing business in India.

Table 2 gives a yearly global competitive index ranking of India by World Economic Forum. We can see the steady growth in terms of its ranking with the rise in score. During the year 2016–17, India was ranked 39th among 138 countries but went down marginally in the current year by 40th rank. However, the economy of the country is expected to grow exponentially with the rise of middle-class society. Globally, the market sized of Industry 4.0 technologies is projected to reach INR 13,90,647 crore by 2023 [18]. Developed countries like the United States, Japan and European countries like Ireland, the U.K., Sweden and Austria have already started accepting Industry 4.0 technologies. However, developing countries like China and India have started late but picking up with initiatives like ‘Made in China 2025’, ‘Make in India 2020’. India being the sixth largest manufacturing country in the world, manufacturing forms an integral part of the Indian growth story.

3.1 Role of Government—As Felicitator

The world is at the edge of the fourth industrial revolution with the advent of innovative technologies such as artificial intelligence (AI), internet of things (IoT), robotics, additive manufacturing, virtual reality, augmented reality, big data, cloud computing and cyber-physical system. However, earlier versions of the industrial revolution brought about systematic implications but what is so different in fourth industrial revolution is much more disruptive and impactful. The effect of fourth industrial revolution on economies and society will be tremendous, rapid and non-linear. The government of India has initiated a slew of policy measures to adopt and accelerate the development and implementation of emerging science and technology to serve its citizens, society and place at large. Taking reference from countries like Germany, China and the US, government could propose a proper regulatory framework, develop competitiveness and form a conducive environment for faster adoption of Industry 4.0 in the country. The government can also develop and establish reskilling centers to fill the skill gaps for successful implementation. As a felicitator, the Government of India should set up a dedicated wing in partnership with private companies to oversee the implementation and promote adoption of Industry 4.0 technologies for sustainable growth. Establishing ‘test labs’ in collaboration with industry bodies, government, academia, labour organizations and provide financial incentives, tax exemptions, subsidies to SMEs in the country to promote faster adoption of Industry 4.0. Table 3 provides a summary of initiatives undertaken by government to promote Industry 4.0 adoption [20].

4 Conclusion

The framework unearthed in this study can be used by researchers, industry leaders and practitioners to assess the readiness and maturity level of organization towards Industry 4.0. Unlike European countries, India can take concrete steps to upgrade the existing small, medium and large-scale industries by providing incentives towards digitization and automation. As a felicitator, the Government of India should set up a dedicated wing in partnership with private companies to oversee execution and promote the implementation of Industry 4.0 technologies for sustainable growth. Establishing ‘test labs’ in collaboration with industry bodies, government, academia, labour organizations and provide financial incentives, tax exemptions, subsidies to SMEs in the country to encourage faster acceptance of Industry 4.0.

Table 3 Government of India's Initiatives towards fourth industrial revolution

Ministry	Initiative	Objectives
Ministry of Heavy Industries and Public Enterprises	National Manufacturing Policy	To foster growth in the market share of manufacturing from current 16–25% GDP by 2022
Department of Industrial Policy and Promotion	National Plan for Manufacturing Clusters	To bring about a convergence in multiple models of development of industrial cluster by Central govt. and state govt. so as to affect better cost efficiency and optimal utilization of resources
NITI Aayog	National Program on AI	To promote AI skill-based education and roadmap in the country
DeitY	IoT	To create IoT industry of 15 billion by 2020 and development of IoT skills
Department of Science and Technology	Mission on CPS	To establish CoE for AI, Robotics
National Productivity Council	CoE IT for Smart Manufacturing	To foster and be as a felicitator for startups, entrepreneurs
Department of Industrial Policy and Promotion	Make in India	To promote foreign investment in India and skill creation within the country
DeitY	Digital India	To digitally empower citizens and create digital society and high-end connectivity across the country
Ministry of Skill Development and Entrepreneurship	Skill India	Upskilling and reskilling of workforce with latest technologies
Department of Policy & Promotion, Ministry of Commerce and Industry	Startup India	To build a strong foundation and ecosystem for startup culture and empower startups to grow
Ministry of Housing and Urban Affairs	Smart City	To promote existing and new cities for sustainable infrastructure, clean and green environment with the application of smart technologies
DIPP, Ministry of Commerce	Invest India	Sector-specific sustainable investment
Foreign Investment & Promotion Board	FDI	To increase foreign investment in 25 key sectors

(continued)

Table 3 (continued)

Ministry	Initiative	Objectives
Ministry of Heavy Industries and Public Enterprises	FAME	Infrastructure and demand creation in EVs and charging stations
Ministry of Science and Technology	National Mission on Interdisciplinary Cyber-Physical Systems (NM-ICPS)	To develop and support research on Cyber-physical systems
Department of Heavy Industry, Ministry of Heavy Industry & Public Enterprises, Government of India	SAMARTH Udyog Bharat 4.0 (Smart Advanced Manufacturing and Rapid transformation Hub)	1.Kirloskar Centre for Learning in Industry 4.0 2.IITD-AIA Foundation for Smart Manufacturing 3.I4.0 India at IISc Factory R & D 4. Platform Smart Manufacturing Demo and Development Cell at CMTI

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Prioritizing Drivers of Industry 4.0 Enabling Additive Manufacturing: A Case Study

Rohit Agrawal and S. Vinodh

Abstract The objective of the study is to analyze the drivers for integrating Industry 4.0 with Additive Manufacturing (AM). In the present study, 16 drivers are identified from the literature review. The drivers are prioritized using Multi-Criteria Decision Making (MCDM) technique namely Analytical Hierarchy Process (AHP). The priority order of drivers is obtained. Based on the priority order, drivers could be focused on effective integration of Industry 4.0 with AM. The implications for practitioners are highlighted.

Keywords Industry 4.0 · Additive manufacturing · Multi-criteria decision making · Analytical hierarchy process · Drivers

1 Introduction

The manufacturing enterprises are preparing towards meeting the challenges of fourth industrial revolution (Industry 4.0). Industry 4.0 is defined as "real-time, intelligent and digital networking of people, equipment, and objects for the management of business processes and value-creating networks" [1]. One of the key technologies facilitating Industry 4.0 is Additive Manufacturing (AM) [2]. AM has several advantages over conventional manufacturing such as customized design, easier generation of complex geometries. Integration of AM process with Industry 4.0 techniques will enhance the process efficiency and provide enhanced services and excellent customization [2]. Various technologies of Industry 4.0 like cyberphysical systems and IoT provides an online support system to AM [3]. In this viewpoint, this paper presents the analysis of drivers of Industry 4.0 enabling AM. The drivers are identified through the literature review. The drivers are prioritized using Analytical Hierarchy

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A. Chakrabarti and M. Arora (eds.), *Industry 4.0 and Advanced Manufacturing*, Lecture Notes in Mechanical Engineering,
https://doi.org/10.1007/978-981-15-5689-0_3

Process (AHP). The priority order of drivers would enable the smooth integration of Industry 4.0 with AM. The article is organized as follows: This section is followed by literature on Industry 4.0 with AM, methodological steps of AHP, prioritization of drivers using AHP, and discussion of results followed by conclusions.

2 Literature Review

Ren et al. [3] integrated 3D printing technologies with cloud manufacturing. They proposed a cloud-based 3D printing model and analyzed the service delivery of 3D printing paradigm model. They also presented architecture design for cloud platform for 3D printers. They concluded that the developed architecture design helped in developing 3D printing clouds.

Baumann et al. [4] proposed the sensor array design for implementation in 3D printers. They included sensors for maintaining and monitoring motion, orientation, and temperature. The presented sensors can be used for remote supervision.

Dilberoglu et al. [2] reviewed the AM advancements along with its contribution towards Industry 4.0. They did a study on three aspects of AM namely, process development, enhancement in design, and recent developments in materials. They argued that AM technologies can accelerate the introduction of smart material also called shape memory alloys to make self-assembly and compact structure. Industry 4.0 helps the designer by providing computational resources which in turn leads to enhanced productivity of 3D Printers.

Baldassarre and Ricciardi [5] aimed towards identifying the importance, use, and benefits of AM technologies which would lead towards the development of Industry 4.0. They prepared a questionnaire and did interviews with 70 Italian labs working on digital manufacturing in Italy. They presented a case study to show the practical uses of 3D printers along with its characteristics and applications.

Qin et al. [6] proposed an Internet of Thing (IoT) framework to continuously monitor and to reduce the energy consumption of an AM process. They presented a case study in which they used the proposed IoT framework to evaluate the energy consumption of an EOS P700 printer.

Flores Ituarte et al. [7] discussed the applicability of digital manufacturing on 3D printers for various engineering applications. They found that SLS based printed parts have the ability to meet the requirements of the automotive sector. They suggested that SLS can be used efficiently when there are lots of variations in parts. They also tested the fatigue life of the printed parts and found that it meets the design requirements.

Wang et al. [8] studied recent development online services related to AM. They proposed a cloud-based AM platform to generate an informative environment for users of product development. The developed platform can aid in providing supports in both design as well as the printing process. They also presented Artificial Neural Network (ANN) method for vision-based identification of surface defects.

Majeed et al. [9] proposed a framework integrating big data analytics with AM to enhance the productivity of AM processes. They did three contributions: first, key component and architecture of big data analytics in AM; Second, development of integration method for big data analytics and AM, and third optimization of production performance of AM performance. They presented a case study, where they optimized process parameters by using big data and ANOVA to minimize energy consumption and to enhance productivity by minimizing build time.

3 Summary

From the literature review, it has been observed that Industry 4.0 techniques accelerate AM processes by providing suitable sensors for monitoring process, simulation software to mimic the actual details before printing parts from 3D printer. Not much research has been done on the integration of Industry 4.0 techniques in AM systems. Industry 4.0 factors enabling AM have not been explored much. Hence, there exists a need to identify the potential drivers of Industry 4.0 enabling AM.

4 Methodology

The aim of this study is to analyze the prominent drivers that aid in integrating Industry 4.0 with AM processes. Analytical Hierarchy Process (AHP) has been used for prioritization of drivers. AHP is a widely used Multi-Criteria Decision Making (MCDM) tool for prioritization of drivers [10]. AHP enables prioritization of drivers by systematical pairwise comparison of all drivers with each other using expert opinion. The pairwise comparison can be made based on expert opinion on how much a factor is more important compared to others. The steps involved in AHP are as follows:

Step 1: Identify the drivers integrating AM processes with Industry 4.0 technologies from literature survey
Step 2: Collect data for pairwise comparison of identified drivers from experts
Step 3: Form a pairwise $n * n$ comparison matrix of drivers based on data collection where n is number of drivers

$$A = \begin{bmatrix} a'_{11} & a'_{12} & \dots & a'_{1n} \\ a'_{21} & a'_{22} & \dots & a'_{2n} \\ \vdots & \vdots & \ddots & \vdots \\ a'_{n1} & a'_{n2} & \cdots & a'_{nn} \end{bmatrix}.$$

Step 4: Develop normalization of pairwise comparison matrix

The normalized matrix is presented below:

$$A^{'} = \begin{bmatrix} a_{11}^{'} & a_{12}^{'} & \ldots & a_{1n}^{'} \\ a_{21}^{'} & a_{22}^{'} & \ldots & a_{2n}^{'} \\ \vdots & \vdots & \ddots & \vdots \\ a_{n1}^{'} & a_{n2}^{'} & \cdots & a_{nn}^{'} \end{bmatrix}$$

$$a_{ij}^{'} = \frac{a_{ij}}{\sum_{i=1}^{n} a_{ij}} \tag{1}$$

where,
i represents row and j represents column [10].
Step 5: Evaluate the eigenvector and corresponding eigenvalues for drivers

$$W = \begin{bmatrix} W_1 \\ W_2 \\ \vdots \\ W_n \end{bmatrix}$$

$$W_i = \frac{\sum_{j=1}^{n} a_{ij}^{'}}{n} \tag{2}$$

where
W is the eigenvector and W_i is the eigenvalue for each drivers [10]
Step 6: Evaluate the ranking of drivers based on their eigenvalue. Finally prioritize the drivers based on their ranking.

5 Case Study

Sixteen influential factors have been considered from the literature survey. The selected factors along with their description are presented in Table 1.

Step 2: Data have been collected from experts for pairwise comparison of drivers in the form of ratings that varies between 0 and 1. From the literature, it has been identified that experts working in the field of AM and Industry 4.0 are very limited [15, 16]. Hence, inputs have been obtained through email from three experts (two academic and one industry). The experts possess experience in AM and Industry 4.0. Inputs have been collected in the form of pairwise comparison matrix and consensus opinion of experts has been used. Saaty scale has been used for pairwise comparison. The pairwise comparison is shown in Table 2.

For normalization of pairwise comparison matrix, Eq. 1 has been used. The normalization matrix is shown in Table 3. The priority of the drivers is ranked based on their eigenvalue calculated for each driver [17]. Eigenvalue has been calculated using Eq. 2. The eigenvalue of each driver is shown in Table 4.

Table 1 Drivers with their description

S. No.	Drivers	Description	Reference
1	Virtual printer control (*D*1)	3D Printer control can be done remotely by providing virtual pool for 3D printer	Ren et al. [3], Qin et al. [6]
2	Virtual printer monitoring (*D*2)	Monitoring can be done online by providing 3D printing services under centralized virtual pool system	Ren et al. [3], Majeed et al. [9]
3	Model format conversion (*D*3)	Cloud manufacturing technique of Industry 4.0 enables an easy way of conversion of various model format	Ren et al. [3]
4	3D model library management (*D*4)	Industry 4.0 techniques provides an easy method for library management of 3D printers. Old design files can be traced and printed easily using the digital library provided with AM system	Ren et al. [3], Wang et al. [8]
5	Online model slicing tool (*D*5)	Online model slicing tool provides an easy way to slice the model in an optimistic way. Slice preview can be seen with different slicing options and selecting the optimized sliced model based on the requirement	Ren et al. [3], Baumann and Roller [14]
6	Virtual 3D printer consoler (*D*6)	The cloud platform in AM can provide easy access to toolkit for 3D printer. With the help of online available toolkit, one can control 3D printer externally	Ren et al. [3]
7	3D printer digital i/o interfaces (*D*7)	Cloud platform deployment in AM enables access to a variety of 3D printer input and output interfaces	Ren et al. [3], Chong et al. [11]
8	Simulation and virtual reality (*D*8)	Virtual reality and simulation is a tool to mimic actual details of print before printing the parts	Chong et al. [11], Wang et al. [8]
9	Cloud computing and manufacturing (*D*9)	Cloud computing and manufacturing is an important Industry 4.0 technology. It provides various applications to 3D printer like online slicing of parts, ease in model format conversion	Chong et al. [11], Majeed et al. [9]

(continued)

Table 1 (continued)

S. No.	Drivers	Description	Reference
10	High-throughput AM systems (*D*10)	High printing speed is one of the major requirement of 3D printer along with minimization of printer deficiencies	Wang and Alexander [12]
11	Open architecture AM systems (*D*11)	It enables the user to understand the principles of 3D printer. It allows the user to do experiment for enhancing the capabilities	Wang and Alexander [12]
12	Instant analytics (*D*12)	Digitalization of AM system with Industry 4.0 provides an instant response to any design related or other kinds of issues	Dilberoglu et al. [2], Chong et al. [11]
13	Collaborative manufacturing (*D*13)	It includes collaboration of online services with 3D printers, collaborative network environment, and collaborative production planning and control	Dilberoglu et al. [2], Chong et al. [11]
14	Customized production (*D*14)	Cyberphysical system integration with AM process can provide excellent customization in products with high efficiency	Dilberoglu et al. [2], Majeed et al. [9]
15	Real-time machine communication (*D*15)	AM system can be connected to network to make web-based AM system. Hence, SMEs can print their parts remotely without owning 3D printer facilities	Dilberoglu et al. [2], Majeed et al. [9]
16	Smart materials (*D*16)	Smart materials are defined as those who change their shape or their properties when are they exposed to external atmosphere. Shape memory alloys are example of smart materials, it can be also called 4D printing materials	Dilberoglu et al. [2], Horst et al. [13]

6 Result

The purpose of the presented study is to identify the prominent drivers integrating AM with Industry 4.0. From the analysis, it is found that "cloud computing and manufacturing (*D*9)" is found to be the most prominent driver. The prioritized ranking of drivers is presented in Table 5. The priority ranking is essential for researchers and practitioners to identify vital drivers for further deployment.

Table 2 Pairwise comparison matrix

	*D*1	*D*2	*D*3	*D*4	*D*5	*D*6	*D*7	*D*8	*D*9	*D*10	*D*11	*D*12	*D*13	*D*14	*D*15	*D*16
*D*1	1	1	3	3	1/3	1	1/3	1/3	1/3	1/3	1	1/3	1/3	1/3	1	1
*D*2	1	1	1/3	1	1/3	1	1/3	1/3	1/3	1/3	1	1	1/3	1/3	1	1/3
*D*3	1/3	3	1	1	1/3	1/3	1	3	1/3	1/3	1/3	3	1/3	1/3	1/3	1/3
*D*4	1/3	1	1	1	1/3	1/3	1/3	1/3	1/3	1/3	1/3	3	1/3	1/3	1	1/3
*D*5	3	3	3	3	1	1	1/3	1/3	1/3	1/3	1/3	3	1/3	1/3	3	1/3
*D*6	1	1	3	3	1	1	1	1/3	1/3	1/3	1/3	3	1/3	1/3	1	1/3
*D*7	3	3	1	3	3	1	1	1	1/3	1/3	1/3	3	1/3	1/3	1	1
*D*8	3	3	1/3	3	3	3	1	1	1/3	1/3	1/3	3	1/3	1/3	3	1
*D*9	3	3	3	3	3	3	3	3	1	1	3	3	1	3	3	3
*D*10	3	3	3	3	3	3	3	3	1	1	3	3	1	3	3	3
*D*11	1	1	3	3	3	3	3	3	1/3	1/3	1	3	1	3	3	3
*D*12	3	1	1/3	1/3	1/3	1/3	1/3	1/3	1/3	1/3	1/3	1	1/3	1/3	1	1/3
*D*13	3	3	3	3	3	3	3	3	1	1	1	3	1	1	3	3
*D*14	3	3	3	3	3	3	3	3	1/3	1/3	1/3	3	1	1	3	3
*D*15	1	1	3	1	1/3	1	1	1/3	1/3	1/3	1/3	1	1/3	1/3	1	1/3
*D*16	1	3	3	3	3	3	1	1	1/3	1/3	1/3	3	1/3	1/3	3	1

7 Conclusions

This article highlighted the need for integration of Industry 4.0 with AM. 16 drivers are being identified and are prioritized using AHP based on experts' opinions. The priority order of drivers is being derived. The top prioritized drivers are cloud computing and manufacturing (*D*9), High-throughput AM systems (*D*10), and collaborative manufacturing (*D*13). Cloud computing and manufacturing is the topmost driver as it provides several online services to AM technologies. High-throughput AM system is one of the reasons behind the growth of AM in industries. AM has the potential to fabricate complex, intricate, and any imaginable part within a short time period. The identification of top drivers would help in analyzing the extent of implementation of Industry 4.0 techniques in AM. The conduct of the study would facilitate the practitioners to focus on drivers for facilitating Industry 4.0 from AM perspective.

Table 3 Normalization matrix

	*D*1	*D*2	*D*3	*D*4	*D*5	*D*6	*D*7	*D*8	*D*9	*D*10	*D*11	*D*12	*D*13	*D*14	*D*15	*D*16
*D*1	0.033	0.029	0.088	0.080	0.013	0.036	0.015	0.014	0.045	0.045	0.075	0.008	0.038	0.023	0.032	0.047
*D*2	0.033	0.029	0.010	0.027	0.013	0.036	0.015	0.014	0.045	0.045	0.075	0.025	0.038	0.023	0.032	0.016
*D*3	0.011	0.088	0.029	0.027	0.013	0.012	0.044	0.129	0.045	0.045	0.025	0.076	0.038	0.023	0.011	0.016
*D*4	0.011	0.029	0.029	0.027	0.013	0.012	0.015	0.014	0.045	0.045	0.025	0.076	0.038	0.023	0.032	0.016
*D*5	0.098	0.088	0.088	0.080	0.040	0.036	0.015	0.014	0.045	0.045	0.025	0.076	0.038	0.023	0.096	0.016
*D*6	0.033	0.029	0.088	0.080	0.040	0.036	0.044	0.014	0.045	0.045	0.025	0.076	0.038	0.023	0.032	0.016
*D*7	0.098	0.088	0.029	0.080	0.120	0.036	0.044	0.043	0.045	0.045	0.025	0.076	0.038	0.023	0.032	0.047
*D*8	0.098	0.088	0.010	0.080	0.120	0.107	0.044	0.043	0.045	0.045	0.025	0.076	0.038	0.023	0.096	0.047
*D*9	0.098	0.088	0.088	0.080	0.120	0.107	0.132	0.129	0.136	0.136	0.225	0.076	0.115	0.205	0.096	0.141
*D*10	0.098	0.088	0.088	0.080	0.120	0.107	0.132	0.129	0.136	0.136	0.225	0.076	0.115	0.205	0.096	0.141
*D*11	0.033	0.029	0.088	0.080	0.120	0.107	0.132	0.129	0.045	0.045	0.075	0.076	0.115	0.205	0.096	0.141
*D*12	0.098	0.029	0.010	0.009	0.013	0.012	0.015	0.014	0.045	0.045	0.025	0.025	0.038	0.023	0.032	0.016
*D*13	0.098	0.088	0.088	0.080	0.120	0.107	0.132	0.129	0.136	0.136	0.075	0.076	0.115	0.068	0.096	0.141
*D*14	0.098	0.088	0.088	0.080	0.120	0.107	0.132	0.129	0.045	0.045	0.025	0.076	0.115	0.068	0.096	0.141
*D*15	0.033	0.029	0.088	0.027	0.013	0.036	0.044	0.014	0.045	0.045	0.025	0.025	0.038	0.023	0.032	0.016
*D*16	0.033	0.088	0.088	0.080	0.120	0.107	0.044	0.043	0.045	0.045	0.025	0.076	0.038	0.023	0.096	0.047

Table 4 Eigenvalue of drivers

Drivers	Eigenvalue
Virtual printer control (*D*1)	0.0389
Virtual printer monitoring (*D*2)	0.0297
Model format conversion (*D*3)	0.0395
3D model library management (*D*4)	0.0282
Online model slicing tool (*D*5)	0.0515
Virtual 3D printer consoler (*D*6)	0.0416
3D printer digital i/o interfaces (*D*7)	0.0544
Simulation and virtual reality (*D*8)	0.0616
Cloud computing and manufacturing (*D*9)	0.1233
High-throughput AM systems (*D*10)	0.1233
Open architecture AM systems (*D*11)	0.0948
Instant analytics (*D*12)	0.0281
Collaborative manufacturing (*D*13)	0.1054
Customized production (*D*14)	0.0909
Real-time machine communication (*D*15)	0.0334
Smart materials (*D*16)	0.0624

Table 5 Prioritization of drivers

Drivers	Rank
Cloud computing and manufacturing (*D*9)	1
High-throughput AM systems (*D*10)	2
Collaborative manufacturing (*D*13)	3
Open architecture AM systems (*D*11)	4
Customized production (*D*14)	5
Smart materials (*D*16)	6
Simulation and virtual reality (*D*8)	7
3D printer digital i/o interfaces (*D*7)	8
Online model slicing tool (*D*5)	9
Virtual 3D printer consoler (*D*6)	10
Model format conversion (*D*3)	11
Virtual printer control (*D*1)	12
Real-time machine communication (D15)	13
Virtual printer monitoring (*D*2)	14
3D model library management (*D*4)	15
Instant analytics (*D*12)	16

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IoT and Semantic-Based Manufacturing System in the Era of Industry 4.0

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Abstract In the current era of Industry 4.0, the focus of academia and industry is to create a smarter and autonomous manufacturing system. In this regard, numerous modifications have been observed in the manufacturing systems from a mass to batch production system and then customized and personalized production. Adoption of several emerging technologies such as the High-Performance Computing, Internet of Things (IoT), Semantic Technology, Blockchain, Digital Twin, and Artificial Intelligence makes a difference between traditional manufacturing enterprises and fourth-generation factories. In this paper, a framework of the manufacturing system is delivered with an integration of the IoT and Semantic Technology to achieve the target of smart factories. Only a small portion of planned work is shown in this paper as an ontological model of Inclusive Manufacturing System with a simple example of Nut-Bolt manufacturing.

Keyword Internet of things · Semantic web · Industry 4.0 · Inclusive manufacturing system

1 Introduction

Manufacturing is one of the vital sectors in contributing to the country's economy by the overall growth of Gross Domestic Product (GDP) along with job creation and inclusive development. At present, a small contribution from the manufacturing

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A. Chakrabarti and M. Arora (eds.), *Industry 4.0 and Advanced Manufacturing*, Lecture Notes in Mechanical Engineering,
https://doi.org/10.1007/978-981-15-5689-0_4

sector is a concerning factor all over the world, especially, in developing countries like India, Brazil, and China where a large population inhabits. In India, the manufacturing sector is not contributing to an expected level. It fluctuates near to 17% of the total GDP of the country whereas the target is to achieve 25% by 2022. Micro, Small, and Medium Enterprises (MSMEs) are considered as a crucial pillar of Indian Manufacturing Sectors because of their enormous share in export as well as overall production in the country, 40 and 45%, respectively, as per India Brand Equity Foundation [1]. The manufacturing systems have been changed from mass production and batch production to customized and personalized production during the transformation from the first industrial revolution to the current era of the fourth industrial revolution known as Industry 4.0 where several emerging technologies are being used. One of the significant contributors to reach this milestone is advancement gained by Information and Communication Technologies (ICT) for improving the connectivity among devices and machines. Such connectivity between devices empowers the automation in industries in several areas including shop floor control, logistics management, interoperability, are a few names. Moreover, internet or cloud technologies perform an abundant role in the integration of manufacturing and service sectors due to proper communication, information sharing, data access, and computing power [2].

In the era of Industry 4.0, resource sharing in a distributed environment, improve quality using embedded technologies, real-time data monitoring, intelligent decision support systems (DSS), maximum productivity and order fulfillment, are the major concerning factors in adopting emerging technologies by MSMEs, but MSMEs feel insecure in accepting these emerging technologies because of inadequate infrastructure, less expected benefits, weaknesses of unskilled labor [3]. Earlier also researchers have proposed several manufacturing systems to tackle the challenges faced by MSMEs, for example, Networked Manufacturing, Agile Manufacturing, Cloud Manufacturing, and Cyber-Physical Production System. In recent, a multi-directional integrated system has been proposed by Singh et al., Inclusive Manufacturing System [4]. Inclusive Manufacturing Systems (IMS) will be best suited to developing countries struggling to increase the contribution from the manufacturing sector in their economy [5]. Previous models tackle the concern individually, for example, networked manufacturing focuses on developing the network among enterprises, cloud manufacturing only discusses the implementation of Information and Communication Technology, and similarly, Cyber-Physical Production System revolves around the concept of virtualization. Whereas IMS encompasses different aspects of societal issues, economic difficulties, and environmental concerns during MSMEs collaboration with the adoption of emerging technologies includes Semantic Web, Cyber-physical system (CPS), Blockchain, and Internet of Things (IoT) with visualization of a digital twin. In the scenario of the degraded environment and imbalance of social and economic growth, the integration of numerous concerns in the development of a manufacturing system can only take developing countries ahead by resolving their issues. In realizing the collaboration among enterprises, data management, information structuring, and knowledge sharing are the need of the time [6]. In the last two decades, the focus of the researchers has been shifted to develop a

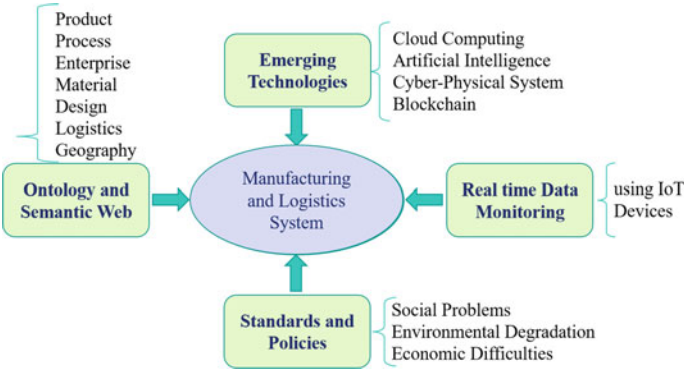

Fig. 1 Framework of proposed manufacturing and logistics system

knowledge-based intelligent system with the adoption of semantic technology. The term Semantic Web was coined by Tim-Berners Lee et al. [7] to create Web of Linked Data. Later on, the research on the concept of Semantic Web and Ontology has been initiated in the manufacturing domain for accessing the information from structured data to achieve the goal of collaboration among distributed manufacturing units.

In the previously published works, researchers have not considered the complete manufacturing system while developing the ontological model and then its further utilization in the semantic web. In this work, an ontological model is developed using Protégé 5.2.0 as a part of the proposed concept of semantic-based Inclusive Manufacturing System. A simulated case study of the manufacturing of nuts and bolts is also presented in this paper for visualizing the working of such a manufacturing system. The overall framework of the proposed work is depicted in Fig. 1 where different segments of manufacturing systems are integrated by addressing various concerns of IMS.

2 Literature Review

A literature review is conducted in the domain of semantic web and ontological framework to manage the information, especially in the manufacturing domain. In the manufacturing domain, various types of data and business management applications practiced since the 1960s, for example, Enterprise Resource Planning (ERP). With the conception of semantic technology, the adoption of Semantic Web and Ontology was started in manufacturing for accessing the information from structured data to achieve the goal of collaboration among distributed manufacturing units. Cecil and Gobinath introduced the concept of the semantic web with mobile agents in manufacturing systems [8]. Labov et al. state that the Semantic web depends on the ontological framework and also describes the solutions for rectifying the responsibilities of vendors participate in the manufacturing systems [9]. Similarly, Lin and Harding investigate numerous ontology-based methods for mapping the proposed manufacturing system engineering (MSE) and different ontologies using web ontology language (OWL) [10]. To give a new direction of customization by using this concept, Jin et al. introduce a design reuse method with engineering application by adopting a semantic web and reuse system for MSMEs [11].

The use of semantic technology in the manufacturing domain has exaggerated the research in distributed manufacturing and collaborative manufacturing especially, for SMEs. Therefore, Zhang et al. deliver a multi-perspective framework for managing the distributed knowledge of the production system on the semantic web by utilizing several modeling languages such as OWL, Unified Modeling Language (UML), and Web Ontology Language—Query Language (OWL-QL) [12]. Similarly, Cai et al. propose a Semantic Web-Based Manufacturing Resource Discovery (SWMRD) system to increase the integration among enterprises by using a multi-level ontological framework and information retrieval method [13]. Ameri and Patil deliver a semantic-based Digital Manufacturing Market (DMM) with consideration of an agile supply chain for improving automation in the system [14]. To achieve the target of rapid production with extensive customization, Lu and Xu propose a semantic-based cloud manufacturing system for maximum utilization of resources by integrating their information in a better manner and easy transfer of knowledge [15]. Similarly, Lin et al. present a new model of a hyperconnected manufacturing system in a collaborative environment with the integration of semantic web and Hadoop approach [16]. Later on, the use of the semantic web has been proposed in the Industry 4.0 scenario by Patel et al. as Semantic Web of Things for Industry 4.0 (SWeTI) where the Internet of Things and Artificial Intelligence were also considered [17]. Ramos presents a review paper on the use of the Semantic Web in Manufacturing by discussing the trends and concerning factors [18]. A few more relevant articles published by several authors in this domain of use of semantic and ontology in manufacturing are given in Table 1.

By going through the literature, it is observed that in most of the articles researchers have considered only a small portion of manufacturing systems such as Furini et al. on Materials, Chhim et al. on Product design, and Wang et al. on Task documentation are a few notable works from Table 1. In this study, an integrated multi-level ontological framework is being developed to fulfill the need for Inclusive Manufacturing Systems as proposed by Singh et al. [4]. In this study, the literature survey is limited to the use of semantic technology where papers related to IoT in manufacturing systems have not been included.

3 Methodology

The proposed Inclusive Manufacturing in our previous work Singh et al. depends on several advanced technologies including the use of IoT devices, Big Data Analytics, Artificial Intelligence, High-Performance Computing, and Semantic Web [4]. To develop the web of linked data and realize the proposed concept, semantic web,

Table 1 Model and domain wise articles on semantic technology in manufacturing

Article	Contribution	Model	Domain consideration
[19]	Explored semantic web for collaborative design by using ontology	Collaborative manufacturing	Design
[20]	Developed an agent-based manufacturing grid using semantic technology in distributed environment		Agent service
[21]	Created an ontology for the functionally graded materials in manufacturing system	Manufacturing system	Materials
[22]	Presented the use of ontology to control the manufacturing system by using semantic web		Manufacturing
[23]	Depicted an ontology of product design and manufacturing process for reusing the information		Product Design
[24]	Proposed an intelligent semantic matching engine in cloud manufacturing by using the OWL-S	Cloud manufacturing	Resource Matching
[15]	Developed a data model, ManuService for service-oriented business using Ontology		Product
[25]	Created an ontology of Design for Additive Manufacturing	Additive manufacturing	Additive manufacturing
[26]	Analyzed the OWL-based approaches for enhancing the manufacturing service capability	Manufacturing service	Manufacturing capability
[27]	Developed an ontology-based knowledge-driven system for planning and verification in Agile Manufacturing	Agile manufacturing	Planning and verification

and ontological modeling are the essential technologies. In the previously published works, researchers have not considered the complete manufacturing system while developing the ontological framework for utilizing in the semantic web. Mainly, researchers have explored some specific domains or segments of the manufacturing system as discussed in Table 1. In this work, the ontology of Inclusive Manufacturing

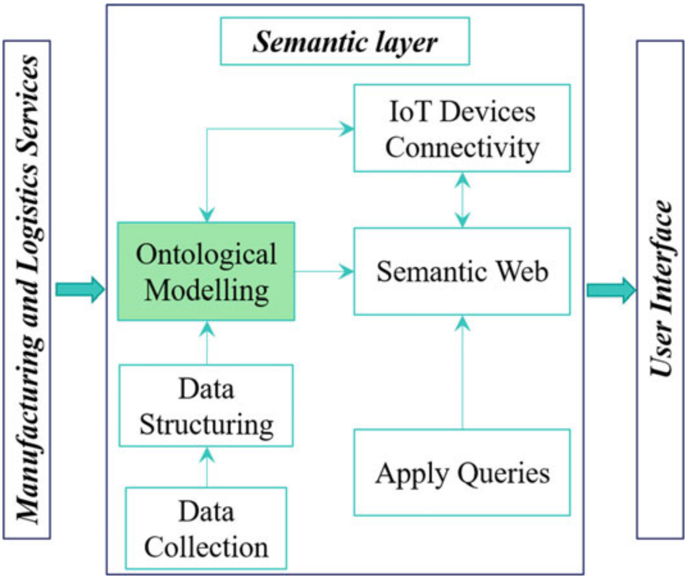

Fig. 2 IoT-based semantic web procedure

System is developed using Protégé 5.2.0. Figure 2 depicts an overall procedure to conduct the proposed work. Mainly, the work spins around the integration of two important technologies, IoT for real-time data monitoring and Semantic Web for accessing the linked data. A simple example of the manufacturing of nuts and bolts has been incorporated in the study to achieve the target of this work as discussed in later sections.

3.1 Semantic Technology

In the era of information and collaborative world, Semantic Technology seems a crucial one for structuring and linking the data for developing an autonomous manufacturing system to fulfill the goal of Industry 4.0. An enormous data is available in a diversified format which needs to be structured in the machine-readable format such that machine-to-machine (M2M) communication will get improved. In realizing, Semantic Web, mainly four segments works include, linked data, vocabularies development, use query languages, and describe interfaces. The eXtensible Markup Language (XML) and Resource Description Framework (RDF) syntax are the W3C standards needed for information integration by using Web Ontology Language. The RDF format follows triplet or turtle structure to define any segment or component of the manufacturing system including services, products, parts, operation, and providers only by three entities named as subject, predicate, and object, for example, Professor → teaches → Students; students → areTaughtBy → Professor; teaches → inverseOf → areTaughtBy. A query language of the W3C standard, SPARQL Protocol and RDF Query Language (SPARQL) are recommended to extract the structured information from the database [28]. The Semantic Web provides a collective platform to stakeholders for maintaining the data in different formats by consolidating several ontological models. For an efficient merge of ontological models, the follow-up of the standard vocabulary is an essential factor. MTConnect delivers a semantic vocabulary to describe the various processes and equipment of a manufacturing system [29].

3.2 IoT Devices

In the current era, Internet of Things (IoT) is ubiquitously available technology and as per Forbes report, the number of IoT devices are extensively increasing and by an estimation, it will be approximately 75.4 billion by 2025 in the world [30]. IoT devices are a combination of internet and sensors in a device, for example, wired and wireless sensor networks (WSN), embedded systems, and Radio-frequency identification (RFID). IoT sensors are going to change the manufacturing environment from the operation level of the shop floor to final delivery of customers because of the integration information system and auto-recovery of dynamic data. IoT system facilitates machine-to-machine communication, information sharing among components, dynamic storage of data on the cloud, robot interaction, tracing of items at the time of manufacturing, storage, and transportation. The dynamical collection of data helps in creating efficient decision support.

3.3 Ontological Modeling

In this paper, for a better understanding of the proposed work, an ontology is created for manufacturing systems using Protégé 5.2.0 with consideration of a small component, Nut-Bolt manufacturing. Nut and Bolt are small and easily available items, but its specifications make a complex task to develop an ontology as depicted in Fig. 3.

This work presents an ontology in the perspective of Inclusive Manufacturing System with the inclusion of four major domains such as Consumer, Logistics services, Manufacturing Services, and System Operator. All these domains have a further division of classes and subclasses as shown in Fig. 4. Beside Inclusive Manufacturing components, two other classes have also been incorporated named products and locations for connecting the information of the system. The information among different individuals and classes are linked using data and object properties. In Fig. 5, an ontology graph is shown where six different types of nut and bolt, 10 manufacturers, eight cities of six Indian states have been considered. Figure 5 depicts only limited information because it is difficult to visualize an ontology graph

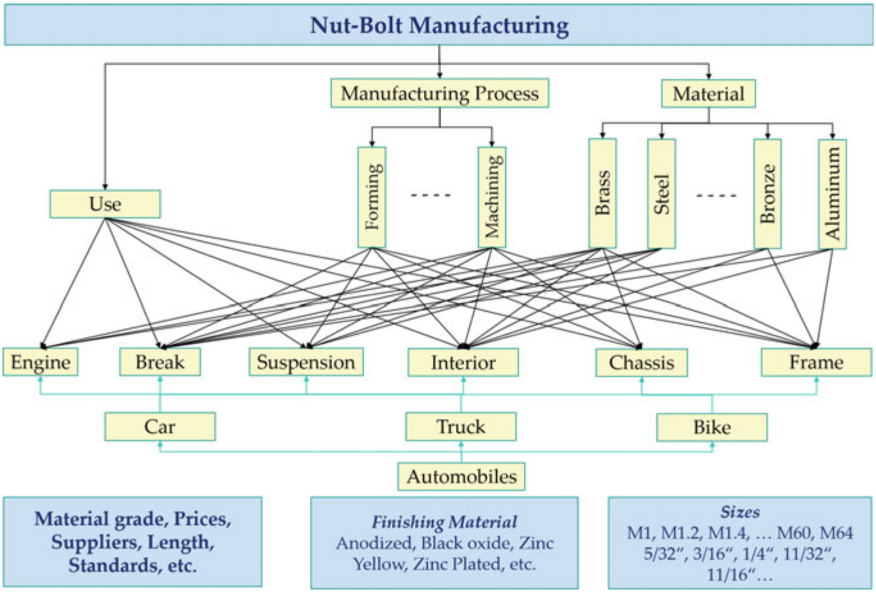

Fig. 3 Information complexity in types of nut and bolts

Fig. 4 Classes and subclasses in developed ontology

of the whole system on a screen. The information can be accessed easily from a syntactic format and thus, RDF syntax is recommended for the semantic web as per W3C standards as depicted in Fig. 6. It helps in extracting the data by applying queries language, like SPARQL and then a decision is taken by DSS by matching the information of customer's quotation with service providers.

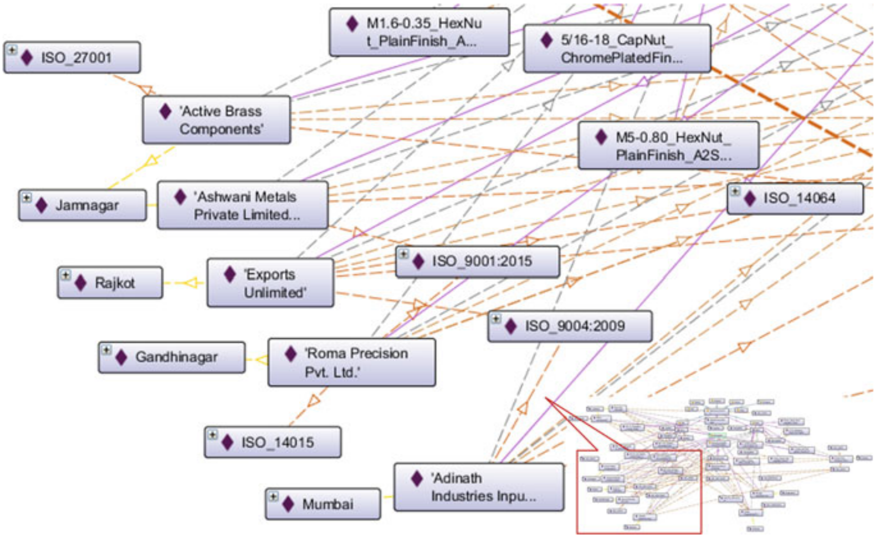

Fig. 5 Ontology graph of presented simulated case study

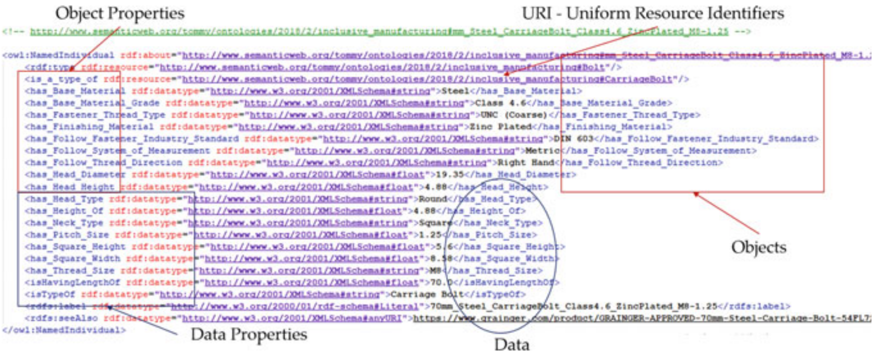

Fig. 6 RDF format of developed ontology

4 Conclusion

The paper is presented inline with the development of Inclusive Manufacturing System by designing an ontology-based information system by merging real-time data monitoring technologies. This work is a part of the planned work of Inclusive Manufacturing System, and the adoption of IoT and Semantic Technology is discussed. In this study, only an ontology of the manufacturing system is highlighted by considering a simple example of nut and bolt manufacturing. Presented work helps in visualizing the complexity of a tremendous amount of data in varied information and gives a direction for its implication in the manufacturing system. In future work, a complete analysis will be done by implementing the concept of IoT integration with the semantic web for capturing the real-time dynamic data.

Acknowledgements The work was supported by the project, E-Business Centre of Excellence funded by Ministry of Human Resource and Development (MHRD), Government of India under the scheme of Centre for Training and Research in Frontier Areas of Science and Technology (FAST): [Grant Number F. No. 5-5/2014-TS.VII].

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Towards Socio-Technical Network Analysis (STNA) in the Connected World of Industry 4.0 and Digital Manufacturing

Vishal Singh and Saeed Mirzaeifar

Abstract Industry 4.0 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, and advanced manufacturing, etc. to improve productivity, quality, flexibility, safety and sustainability across manufacturing enterprises and production environments. Building on this approach, there is also a greater promise of transformation in other industries such as construction and shipbuilding which have traditionally been laggards in direct digital manufacturing. Nonetheless, in order to be able to leverage the connected intelligence of the socio-technical network, we need corresponding tools and methods for Socio-Technical Network Analysis (STNA) and facilitate coordination and transaction of data, information, and knowledge between the distributed systems. This paper discusses the steps towards a framework for STNA in a connected design and manufacturing environment, especially focusing on assessment of transaction of data, information, and knowledge between the constituents of the distributed system.

Keywords Socio-technical system · Human–machine interaction · Socio-Technical network analysis (STNA) · Transactive memory systems (TMS)

1 Introduction

The Industry 4.0 paradigm is believed to be a transformative paradigm not only in the traditional manufacturing sector, but across most other industries that will benefit from the connected intelligence of distributed socio-technical systems including people, computer-aided design and engineering tools, information systems, sensor

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A. Chakrabarti and M. Arora (eds.), *Industry 4.0 and Advanced Manufacturing*, Lecture Notes in Mechanical Engineering,
https://doi.org/10.1007/978-981-15-5689-0_5

networks, intelligent devices and equipment, and robotics and advanced manufacturing approaches such as additive manufacturing. Such a solution is envisioned to be a distributed system, where the data, information, and knowledge of the tracking, monitoring, control, and execution of the various functions and activities in the production environment will be distributed across different constituents of the systems. The constituents of the system will need to effectively communicate and coordinate such that the right information is available to the right actor at the right time for timely action. Unlike the traditional manufacturing and production systems where the actor typically referred to the human actors, in the Industry 4.0 paradigm we expect greater autonomy of computational and robotic systems, extending the set of actors beyond human users to include autonomous and semi-autonomous systems and machines. Consequently, the promise of improved productivity, quality, flexibility, safety, and sustainability across manufacturing enterprises and production environments resulting from the use of Industry 4.0 also depends upon the coordination, information flow, and transactions between the constituents of the socio-technical system.

Since, the data, information, and knowledge of the collective are distributed across the different constituents of the aforesaid system, we can also conclude that the system requires distributed knowledge management (KM). For the constituents of systems, we use the term "KM sources" to refer to them as sources that store or provide either knowledge, information, or data for the effective functioning of the system.

In particular, we discuss the case of the construction sector where Industry 4.0 is also expected to bring about a transformative change in the production system, enabling a direct digital construction era, which would bring the construction production practice closer to the manufacturing sector [12]. The paper focuses on types of actors (KM sources) in such a distributed socio-technical system and lists a set of characteristics that can provide useful insights into the management and coordination of the distributed data, information, and knowledge. While the discussion on the production system and the characteristics is built around the construction sector, we argue that the type of KM sources and the set of characteristics discussed in this paper also apply to most production systems across industry boundaries.

2 Background

Besides the project personnel who need to coordinate their knowledge and skills, a digital construction project in the Industry 4.0 paradigm includes several KM sources across which the project-related knowledge, information, and data are distributed. These include Building Information Modeling (BIM) applications, other Computer-Aided Design, Engineering and Manufacturing (CAD/CAE/CAM) tools and applications, and other information systems. In addition, other systems and devices such as construction equipment, robots, sensors, beacons, and electronic tags are used as sources of data related to the project. Besides these digital sources, analog sources such as paper documents, books, and visual management boards may still continue to

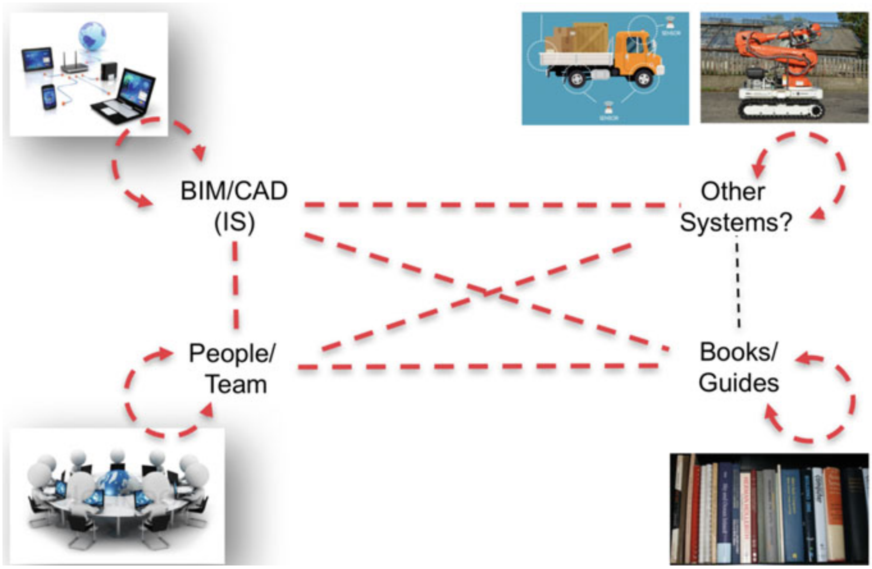

Fig. 1 Connected KM sources in socio-technical systems across which data, information, and knowledge is distributed

be used. Therefore, the success of a digitalized construction project in the Industry 4.0 paradigm will depend on effective coordination and transaction of data, information, and knowledge across this network of distributed KM sources, Fig. 1.

2.1 The Socio-Technical Network in Digital Construction

The different KM sources in a digital construction project can be categorized as human (people, teams and organization), information systems (including BIM, CAD/CAE/CAM, all other ICT systems), electronic and hardware systems (Building Automation Systems—BAS, Internet of Things—IoT, robots, fabrication tools, etc.), and analog systems (paper documents, drawings, visual management boards, etc.). Based on this generic categorization, the following types of dyadic information exchange and transactions are identified, Table 1.

H2H includes transactions between the project team members, and between teams and organizations, including other stakeholders.

IS2IS refers to the information exchange and transactions between different BIM applications, CAD systems, database management systems, project data banks, document management systems, Enterprise Resource Planning (ERP) systems, and any other ICT systems being used in the project. Communication media such as emails and messaging systems can also be categorized in this group.

Table 1 Different types of dyadic transactional links in digitally mediated construction projects

Codes: transactions and distributed memory
H2H: human to human transactions
IS2IS: information system (IS, including BIM, CAD, databases, etc.) to information system
H2IS (or IS2H): human to IS
S2S: system (BAS, IoT devices, robotic systems, fabrication systems, sensors, etc.) to System
S2IS (or IS2S): system (IoT devices, robots, sensors, etc.) to IS (including BIM, CAD, etc.)
H2S (or S2H): human to system
H2A (or A2H): human to analog systems (paper documents, visual management boards)

H2IS/IS2H refers to the transactions between the human users and IS through Create Read Update Delete (CRUD) operations.

(Electronics/Hardware) System to (Electronics/Hardware) System (S2S): These systems refer to a wide range of systems including BAS, IoT devices, sensors, robotic systems, fabrication systems and machines, intelligent building elements and construction equipment, etc., that may store and exchange information and data relevant to the project. These systems may not only provide information or data but may also have an inbuilt knowledge-base and inference engine for edge computing.

S2IS/IS2S refers to the transactions between the BAS, IoT, robots, machines, and other hardware systems with different IS including BIM applications, ERP systems, messaging systems, etc. The S2IS interaction is not only important for automated decision processes, control and tracking, documentation, and acquiring new information and insights but also to enable better interaction with human users.

H2S/S2H refers to the direct transactions between users and hardware systems, which could relate to information and data read and input through input/output devices, display panels and dashboards of such devices and machines, meter readings, auditory signals alarms, etc.

H2A refers to transactions between users and all the information sources that are not digitized or digitalized so far, for example, paper documents and files, paper-based books, guidelines and reports, and visual management boards and signages on sites.

Such a production environment with these transactional links creates a Transactive Memory System (TMS), where the knowledge, information, and data of the collective system remains distributed across multiple sources. Hence, we adopt a TMS perspective as the basis to assess the socio-technical network.

2.2 *Transactive Memory Systems (TMS)*

Transactive Memory System (TMS) concept has been used across both human and computational systems to understand and explain the management of distributed KM sources, including encoding, storage, retrieval, and update of knowledge across different sources [18, 20, 19, 21].

In the context of organizations and teams, TMS has been used to understand and explain group work, the formation of shared understanding, and coordination of tasks and specialist knowledge and expertise of team members [2, 3, 4, 5, 9]. TMS allows groups to collectively encode, store, and retrieve knowledge [1, 11, 18, 20], and deal with tasks that require coordinating the specialized competence and knowledge of the team members [15].

In the context of information systems and computational systems, TMS has been used to understand and explain the strategies for encoding, storage, retrieval, and update of information and data, besides the management of memory space, processing power, and connectivity [20].

For effective coordination of the distributed knowledge, information, and data across a TMS, several characteristics and factors have been discussed in the literature. Some of these key characteristics found suitable for this study include

Connectivity and access. Different constituents of the TMS should be able to share and access knowledge, information or data as and when required, following the agreed protocol. It is also desirable that the connection is reliable and robust, allowing immediacy and consistency [1, 5, 6, 7, 20].

Allocation, sharing, and redundancy. Allocation of memory resources is required to avoid redundancy, and facilitate complementarity [1, 7, 18, 20].

Accuracy, credibility, reliability, and trustworthiness. The accuracy, credibility, reliability, and trustworthiness of the different KM sources are critical for the effective functioning of the system [10, 20].

Reinforce expertise. In a TMS, each KM source becomes recognized for its specialized knowledge, information, or data domain. Consequently, when new knowledge, information, or data is acquired in a TMS, it is desirable that the relevant knowledge, information, or data is directed towards the specific KM source that is recognized for the domain [1, 2, 6, 13].

Centrality. Centrality is an important measure of any distributed system, which indicates which nodes or KM sources are central to the distribution and access of the knowledge, information, or data across the TMS. Centrality can help identify the bottlenecks and critical resources and plan information exchange links and pathways [14, 17].

Information quality/loss in transfer. There may be a loss of information quality during the transfer and exchange between the different sources. The loss of information quality during transfers and transactions can occur due to representational differences, lack of shared understanding and common ground, incomplete transfer, and so on [6].

Updates and relevance. The different constituents of a TMS should have updated and relevant knowledge, information, and data, both about the content relevant to their designated topic or role, as well about the updates and changes happening across the other sources within the TMS [1, 2, 6, 13].

Backup. It is imperative to have backup mechanisms such that loss or failure of one or more sources does not jeopardize the functioning of the whole system [13, 20].

Directory. It is important who knows what, and how to have access to the right people at the right time. This has traditionally been managed using telephone directories, yellow pages, and mailing lists. Thus, directories create shared resources that map the knowledge distribution in the system for common reference [15, 18, 19, 21].

The identified characteristics can be used to assess a socio-technical network in terms of its TMS capabilities.

3 Towards Measures for Socio-Technical Network Analysis

Traditionally, it is not common to conduct a comprehensive Socio-technical Network Analysis (STNA), because, despite the existence of a socio-technical system, decision-making and autonomy have primarily been associated with human networks. As a result, in the traditional production systems, separate analysis of distributed technical systems, information systems, and social systems have existed, but the collective network has rarely been given attention. For example, in terms of information systems there is considerable prior work on assessing information flows, coordination and exchange in BIM and Product Lifecycle Management (PLM) systems [8, 16, 22], while in social systems approaches such as Social Network Analysis (SNA) have been used to assess information flows, coordination and exchange in project teams, stakeholder networks, and organizations.

Therefore, with increasing reliance on technical and information systems, and greater use of autonomous non-human agents in the Industry 4.0 paradigm, we argue that the advances in the understanding of distributed systems, TMS, and social networks can be combined together and leveraged to develop measures for STNA.

3.1 Building on Measures Used in Social Network Analysis

Several measures for SNA have been established over the years, with considerable research and practical applications across different disciplines [14, 17]. Often the purpose of such an analysis is to understand the structural and functional attributes of the social network, with the aim to assess gaps and dependencies in the network. Some of the common measures used in SNA include network density, centrality, tie strengths, modularity, structural holes, homophily, reciprocity, etc. SNA can be used to assess various aspects of the network, and hence, one of the key requirements for the analysis is to choose the relevant characteristics of the nodes and links in the network on which the evaluation of centrality, homophily, density, and tie strengths are determined. For example, SNA based on a single factor such as trust can reveal the network structure and distribution in terms of trust in the assessed network, or a multi-factor SNA can be conducted where the links and nodes are evaluated either as a weighted outcome of multiple factors or as a multiplex network that juxtaposes the network structure separately for each of the factors or characteristics.

Nonetheless, before we decide whether to approach the assessment as a multiplex network or a single network with weighted results, the first step is to determine the characteristics or factors on which to assess the STNA. Since we are interested in understanding the socio-technical network from a TMS perspective, we propose to use the characteristics of a TMS as the factors of interest for STNA.

3.2 Assessment Matrix

Based on the identified TMS characteristics, and the constituents of a TMS in the digital construction projects and the corresponding links, we propose that the first step towards STNA is to create an assessment matrix with the TMS characteristics mapped against the different KM sources and their corresponding links, Table 2.

It should be possible to use the proposed assessment matrix for both qualitative as well as quantitative assessment. Even the qualitative assessment can lead to tangible numbers based on the use of Likert Scale or similar approaches. Consequently, it should be possible to map the network and assess the nodes and links based on the obtained scores and numbers.

Table 2 Assessment matrix towards socio-technical network analysis from a transactive memory systems perspective

	H2H	IS2IS	H2IS	H2A	S2IS	H2S	S2S
Connectivity and access							
Allocation, sharing, and redundancy							
Accuracy, credibility, reliability, and trustworthiness							
Expertise reinforcement							
Centrality							
Information quality/loss in transfer							
Updates and relevance							
Backup							
Directory							

4 Discussion and Conclusions

This paper presents a preliminary framework for Socio-Technical Network Analysis based on the recognition that the Industry 4.0 approach is premised on the connected intelligence of the distributed socio-technical systems, but we currently do not have adequate measures to analyze the socio-technical network from the perspective of distribution, sharing, coordination and transactions of data, information, and knowledge between the different constituents of the system.

The proposed framework builds on the characteristics of TMS perspective, which appears to be a suitable approach to view the management of distributed data, information, and knowledge in a connected and distributed socio-technical system envisioned for Industry 4.0.

The framework is currently based on theoretical work, while testing the usefulness of the framework in practice is currently underway in two pilot projects. The findings from these pilot studies and their implications on future research will be presented in a follow-up paper.

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Intelligent Analytics for Factory Energy Efficiency

M. Srikanth, S. Prasanth, T. Viswanathan, and C. S. Ram Shankar

Abstract Energy Analytics for factory energy efficiency is one of the key improvement processes for machinery and equipment in the establishment of smart manufacturing. Currently, the manufacturing industries need upgrade towards the benefits that extend beyond just the production of goods into functions like planning, supply chain logistics, and even product development. Energy flexibility and efficiency are becoming more important than just automation. Energy consumption reduction and sustainability are important for companies concerning the high price for energy and the planned phasing-out of nuclear power. Strategies need to be framed to overcome these obstacles. This paper discusses real-time problems through a case study that includes descriptive, diagnostic analysis and explains further about the impacts of building predictive analytics for the energy system.

Keywords Automation · Smart manufacturing · Energy flexibility · Energy efficiency

1 Introduction

Smart manufacturing operations adopt the physical and cyber technology combination and integrate the already existing independent discrete systems to be more complex and achieve high precision than before. Evolution in manufacturing technology through the development of cloud-based enterprise, information technology, data mining, and data visualization made us move from just digital to intelligent analytics for factory energy efficiency.

Currently, intelligent manufacturing technology is the high-end technology where industrialized countries pay more attention to Europe 2020 strategy [1],

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A. Chakrabarti and M. Arora (eds.), *Industry 4.0 and Advanced Manufacturing*, Lecture Notes in Mechanical Engineering,
https://doi.org/10.1007/978-981-15-5689-0_6

Industry 4.0 strategy [2], and China manufacturing 2025 [3]. Reindustrialization and manufacturing reflow has been highly accelerated in the United States [4].

The future manufacturing is intrigued by the intelligent analytics and transformation worldwide. One side involves a variety of changes and challenges demanded by the Industry 4.0 and companies are on the verge of facing it. The planned phasing-out, the increasing price of energy are dealt with by companies today. These obstacles need to be handled by establishing measures to mitigate energy consumption and improve energy efficiency. Transparency needs to be achieved in terms of the energy consumption of the machines. Energy analytics, i.e., examining raw data to derive conclusions from the energy data, is a key enabler for implementing Smart Manufacturing [5]. Solutions for energy analytics need to be carved systematically through descriptive, diagnostics, predictive, and prescriptive analytics to derive insights for known and unknown problems [6].

In Smart Manufacturing, analytics need to be performed in the desired manner due to the availability of insurmountable data (volume), structure and unstructured data (variety), highly responsive toward decision-making (velocity). Accurate and timely insights need to be enabled for better decisions by utilizing big data infrastructure.

1.1 Energy Analytics

The energy analytics within companies is achieved by intelligent analytics for factory energy. The preventive measure and control are derived by intelligent analytics for factory energy to ensure the energy supply of a company while respecting the economic and ecologic aspects. To be effective, energy analytics programs should include main sections: (1) Descriptive analytics; (2) Diagnostic analytics (3) Predictive and Prescriptive analytics. We will discuss here primarily on the first two analyses made for energy analytics in Industry 4.0 with a case study.

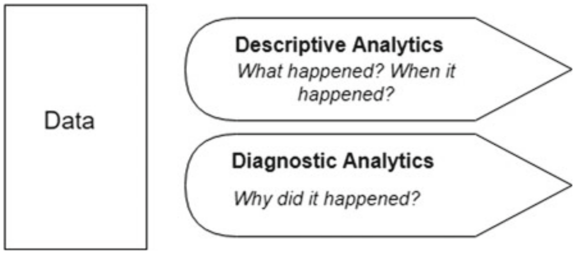
2 Methodology

2.1 Descriptive and Diagnostic Analytics

It is the study of collected energy data to analyze the characteristics. The data contains information to be studied meticulously and insights need to be derived (Fig. 1).

The insights herein deal with the scope to bring down the cost and energy consumption to an optimized level. The steps involved are two as mentioned in the above diagram. ***Step 1***: Descriptive Analytics will interpret the historical data to give clarity over the happenings in the past of a machine to make us know *what happened.*

Fig. 1 Steps for analysis



Step 2: Diagnostic Analytics is an advanced analysis to derive the characteristic by techniques like data drill down, data mining, correlation within data, etc., to make us understand *why it did happened?*

2.2 Benefits of Energy Analytics

Various advantages can be accomplished through energy analysis. Some of these includes [7]:

- Reducing energy consumption and increase sustainability.
- The decrease in operating costs (approximately 20–30%) by systematic analysis.
- Overall performance of the total system and the productivity, profitability can be improved.
- Depletion rate can be decreased towards natural resources and demand-supply narrow gaps.
- Avoid unexpected equipment failure.

3 Case Study

One of the leading discrete manufacturing industries in India wants to convert each of its manufacturing facilities to Smart Manufacturing.

The block diagram (Fig. 2) is the abstract representation for the establishment of smart connected and operation replacing the traditional manual interventions to manage the manufacturing industry. Descriptive analytics performed towards increasing the efficiency of energy through intelligent analysis using the approach namely *Pareto analysis.*

It is a statistical approach in decision-making utilized for the selection of a fewer number of tasks that will make a significant overall effect. Utilization of Pareto Principle (otherwise, called 80/20 rule) is to generate 80% of the benefit from the entire job by working on 20% of the work. This method is also called the vital few and the trivial many. This method identifies the top causes that when addressed to resolve the primary portion of problems.

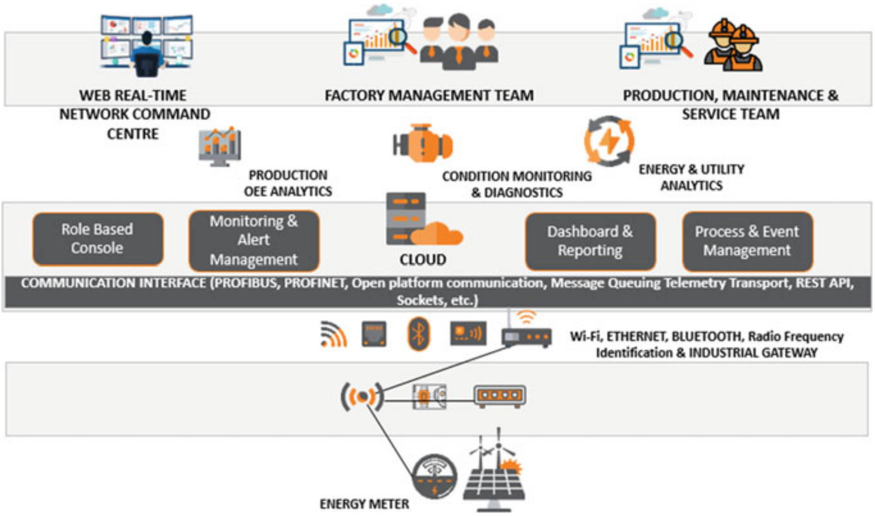


Fig. 2 Schematics architecture

4 Energy Analytics Audit

The current system is digitally enabled to display machine running/idle status, production status, energy status, and many other aspects of the production system. There are about 40 energy meters installed on the premise to monitor the amount of energy consumption.

The Pareto analysis will help us to identify the major energy-consuming machines.

The energy data were acquired from all energy meter for October, November, December months of 2018. The top energy-consuming department was identified using—**Pareto Principle** in Fig. 3.

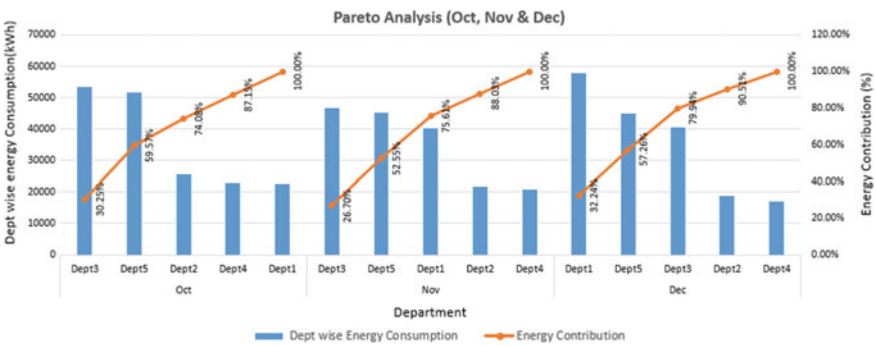


Fig. 3 Pareto chart analysis

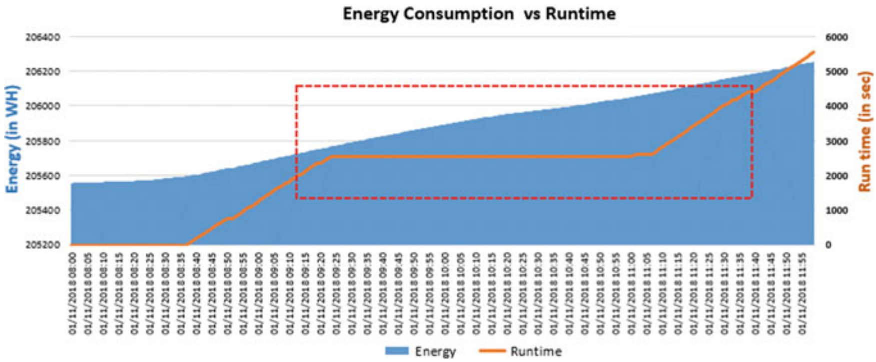


Fig. 4 Energy consumption versus runtime

From Pareto chart analysis, **Dept 3** was identified as one of the significant energy-consuming departments as per Fig. 3 and energy analysis was performed.

The instantaneous data for Dept 3 was taken and energy analysis was performed. The energy data was correlated with runtime and energy loss areas were identified.

From further analysis, certain Energy reduction scope areas were listed below,

- To identify areas where production is not happening in relation to downtime reasons, but still, energy is utilized.
- To optimize usage of energy in the machine, when it is in idle state.
- To calculate energy consumption ratio with respect to the production and to reduce energy level.

From Fig. 4, it is inferred that energy is being consumed when the machine is not running.

5 Impacts of Energy Loss

The energy consumption analysis (Fig. 5) chart is plotted using minute-wise data. The graph depicts the amount of energy consumed when, Part Production, machine running with no production, machine was Idle for October, November, December 2018.

The energy consumption when (1) Machine running with no production and (2) Machine Idle were classified as energy waste areas. Thus, the energy waste for three months accounts for loss of **₹5, 31,769**. (*Assuming ₹.7/kWH, the below cost analysis is performed*)

Table 1 is the detailed cost analysis made with respect to Fig. 5.

The total cost analysis audit for the three months was found to be **₹10, 67,052** from the table. This observation makes us identify that **49.83% of energy loss** occurs

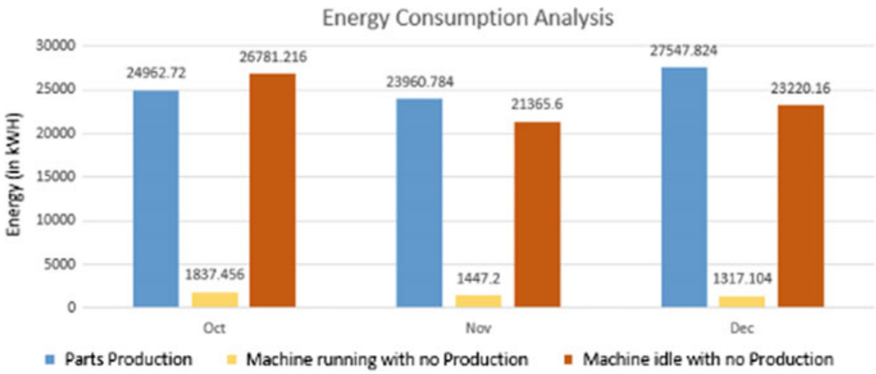


Fig. 5 Energy consumption analysis

Table 1 Energy cost analysis (minute-wise data)

Month	Parts production	Cost (Rs.)	Machine running with no production (kWh)	Cost (Rs.)	Machine idle	Cost (Rs.)	Total cost (Rs.)
OCT	24,962	1,74,734	1837	12,859	26,781	1,87,467	375,060
NOV	23,960	1,67,720	1447	10,129	21,365	1,49,555	327,404
DEC	27,547	1,92,829	1317	9219	23,220	1,62,540	364,588
Total	76,469	5,35,283	4601	32,207	71,366	4,99,562	1,067,052

considering the machine idle and machine running with no production. This could be a significant start for building an intelligent analytics system for this factory.

6 Summary and Conclusion

Energy analytics is an intelligent production system wherein [8], we could concentrate on energy data through the statistical approach involves intelligent analytics for factory energy.

This paper discusses the energy analytics audit towards the different levels of impacts made by energy data. It was understood through a case study about the real-time energy audit using the Pareto analysis. This approach we discussed will help us to address the major portion of the energy impact in descriptive analytics. In near future, to mitigate the cost, energy and to build sustainability in the system, an intelligent analytics for factory energy can be initiated in the primary portion of waste energy consumption areas through the findings made.

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Smart Multi-material Weight Tracking Resource Bin

Puneeth S. Kannaraya, S. Dilip, Chandana S. Deshpande, Manish Arora, and Amaresh Chakrabarti

Abstract Smart Manufacturing or otherwise Industry 4.0 as known in Europe has been the latest technological trend in all industry domains. The components being cyberphysical system (CPS), Industrial Internet of things (IIoT), Big Data are major key technologies in improving the overall performance of the factory. In this paper, a case study is done to understand the resource management for medical device manufacturing company and with bringing smartness into manufacturing. A smart multi-material tracking resource bin that measures the quantity of the waste materials is designed and developed which can send real-time information across the stakeholders using the components of smart manufacturing. The application of the resource bin will then may result in the cost-cutting and increasing productivity which are important measures for Micro, Medium, and Small-scale Enterprises (MSME).

Keywords Smart manufacturing · Waste · Weight · IIoT

1 Introduction

Smart manufacturing systems include instrumentation systems, condition monitoring systems, manufacturing execution systems, and process control systems [1]. Smart

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A. Chakrabarti and M. Arora (eds.), *Industry 4.0 and Advanced Manufacturing*, Lecture Notes in Mechanical Engineering,
https://doi.org/10.1007/978-981-15-5689-0_7

manufacturing promises quality at greater safety and productivity [2] at a lower cost and environmental impact.

The overall goal of our research is to understand the major manufacturing challenges in the medical device industry in India, especially in Micro, Small, and Medium Enterprises (MSMEs), and develop means to support these typically conventional enterprises to adopt smart manufacturing. A large number of MSMEs in India are in shortage of funds and have limited access to relevant information. By trying to reduce costs and minimizing capital expenditure, the MSME sector is dormant when it comes to the use of the latest technology and knowledge [3]. In accordance with the provision of Micro, Small and Medium Enterprises Development (MSMED) Act, 2006, the MSMEs are divided into two classes: Manufacturing Enterprises and Service Enterprises. The manufacturing enterprises are defined in terms of investment in plant and machinery. The limit of investment for micro, small, and medium enterprises is up to 10 Crore INR. Similarly, for enterprises engaged in providing or rendering services, the investment in equipment limited to 5 Crore INR [4].

As part of the objective, this paper reports a detailed case study conducted in an orthotic footwear manufacturing MSME, which manufactures customized footwear for people suffering from diabetic foot, corns, calcaneal spurs, heel pain, heel cracks, metatarsal pain, arch pain, obesity, height difference, low back pain, and flat feet. Manufacturing companies typically procure huge quantities of raw materials; when these raw materials flow into the production line, the factors such as keeping track of materials, accounting the raw materials consumed, and waste materials generated becomes crucial in terms of cost [5] and efficiency in any manufacturing industry. MSMEs in India, especially its micro variety is highly cost-sensitive; hence there is a need to introduce an affordable technology in the production line to monitor the usage of raw materials. Affordability to high-end technology becomes a challenge and often results in using nonstandard practices.

Medical device manufacturing industry generates various types of waste in its manufacturing sites, research institutes, and health care facilities. These include the types of waste generated by medical footwear manufacturing unit, including raw material waste during production activities. Over the last two decades, the footwear sector has placed significant effort in improving material efficiency as well as eliminating the use of hazardous materials during the production phase [6]. However, unsustainable consumption patterns of raw materials in its production lines generate considerable waste.

There are several methods to supervise the waste generated; the most common method would be to track the weight of waste material produced; an example being, use of weighing scale in beehive monitoring [7], and being accountable for the same. There are, however, no appropriate methods used in the MSME for this purpose, let alone tracking the weight of waste on a continuous basis in an accurate and stable manner.

Henceforth, in this paper, a highly economical solution for multi-material weight tracking has been presented; the solution uses an industrial-grade weighing system, around which the functionality of tracking different types of waste materials which are being generated, measured on a single weighing platform has been developed.

2 Case Study

As mentioned earlier, the intent of this work is to study and understand the processes and activities involved in the micro/small/medium scale medical device manufacturing industry, carry out time study for their value-added and non- value-added activities, so as to find out the existing bottlenecks in their processes and help them to improve the productivity of the enterprises using smart manufacturing technologies.

The detailed study carried out in the orthotic enterprise spanned from the event when an order is received all the way to the packaging of the product. Once an order is raised, raw materials from the inventory are issued to the production stations where manual cutting and stitching and gluing are carried out. There are around 40 different materials used in the manufacturing of a shoe [8]. Typically, shoes are cut from large sheets into patterns, leaving 30% or more material to be discarded [6]. There will always be some waste that cannot be prevented at the source. Where waste material is produced, an optimal end-of-life treatment option must be selected with the lowest possible risks to human health and the environment. Table 1 shows the footwear waste generation for different materials in India.

At present, the waste collected is discarded to the landfill, leaves a major carbon footprint on the environment. Landfill sites can result in serious environmental pollution of groundwater and rivers, caused by landfill leachate [8]. But for optimal usage of the raw materials and recycle and reuse of the wastes by following a scientific procedure can reduce the effect on the environment.

For cutting the upper part and the insole materials Ethyl Vinyl Acetate (EVA) sheets are used; during each of these stages, waste is generated (see Fig. 1 for the different parts of footwear). In a similar manner, waste is generated at most of the manufacturing stations. Based on the study of the shoemaking process in the above manufacturing unit, it has been clear that raw materials are currently not used to the maximum due to inefficient, manual intervention in the unit. If the amounts of materials wasted, their locations, and associated processes can be tracked across the production lines, the costs associated with the material losses can provide motivations for devising and implementing measures for their improvement, in particular, by

Table 1 Condition of footwear waste in India (Contribution of various elements in generating waste) [8]

Footwear materials	Percentage (% wt)
Leather	25
Polyurethane (PU)	17
Thermoplastic rubber (TR)	16
Ethylene vinyl acetate (EVA)	14
Poly Vinyl chloride (PVC)	8
Rubber	7
Others (adhesives, metals, etc.)	7
Textiles and fabrics	6

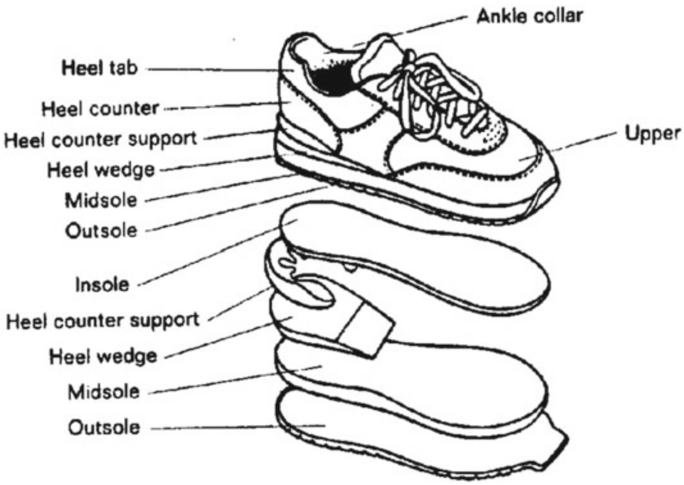

Fig. 1 Parts of footwear (reference image)

avoiding material losses. One way to tackle this challenge is to develop a high-quality weight tracking system that is also highly affordable.

3 Methodology

By the emergence of fourth industrial revolution or smart manufacturing, the manufacturing processes have opened to broad ways by allowing advanced technologies with the use of IIoT, CPS, Big Data, etc. These technologies which have the capability of data transformation and informatics will help manufacturers to expose to the competitive market with better business strategy. Also, it allows to penetrate the market with cost-effective products and also improve the efficiency of production.

One such approach was decided to apply for the tracking of waste materials and to quantify it so then the information can be used to extrapolate the efficient use of raw materials as per the interest of stakeholders.

There is a certain amount of research has been gone through for waste management in various municipal infrastructure services, for smart cities. But we don't see much usage of waste management techniques by using smart manufacturing concepts in the industrial sector. Although the idea of sensors-based waste bins [9–11], capable of notifying waste level status, is not new to its entirety, however, to quantify the collected waste on the basis of the material is what concerned. Use of Radio Frequency Identification (RFID) technology for the bin identification has also been used [11, 12].

The difficulty in the maintenance of the RFID tags post-production in our case study is another issue. So the usage of barcodes which can easily be printed onto the

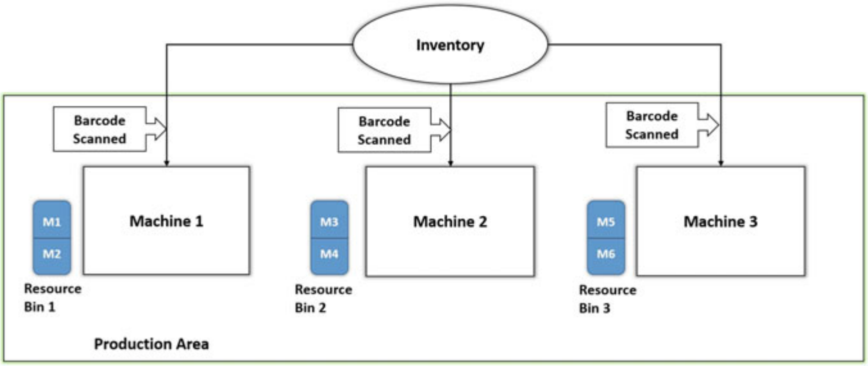

Fig. 2 Activity flow in factory layout

paper, allowing to be assessed by a worker for a particular job order with material and human information, was decided. Whenever the job order is issued and materials are collected from inventory the barcodes are to be scanned. This enables the traceability of the materials at the cutting stations. Figure 2 shows the resource bins placed beside the cutting machines and barcode reading activity happens before raw material enters into the production line.

4 Design

4.1 Hardware Design

The smart multi-material resource bin is designed to be placed at one of the cutting stations, where large sheets of 1.5 m × 4 m are placed on the table and a hydraulic press shear off the sheets into soles of sizes determined according to the shearing die placed beneath. The waste generated is then put into the nearby bins designated for that type of material.

In order to identify the type of material used during any part of the production, barcodes are attached to each batch of raw materials. To scan these barcodes, a barcode scanner is used, which scans the encrypted data and sends it to the visualization platform, the Node-RED.

As mentioned earlier, during the manufacturing process of these orthotic shoes, different types of raw materials are used. There is a need for different materials to be tracked on a single weighing platform so that variants of the same resource bin can be developed and placed according to the disposal flow with appropriate barcodes to facilitate the materials associated with each bin at each location as shown in Fig. 2.

The weight of the two sets of waste materials tracked independently on a single weighing platform is given by the following equation:

$$T1 = w - p - T2 \tag{1}$$

$$T2 = w - p - T1 \tag{2}$$

where

$T1$ weight of material type 1
$T2$ weight of material type 2
p tare weight
w applied weight

The smart resource bin has been designed to collect two different types of waste materials (and can be extended for collecting more types if needed) with two separate bins for waste collection. The parting door provided for the resource bin ensures that a given waste can be slid into its designated bin by the door closing the other bin. A DC motor is used to operate the door with two limit switches attached on either side of the motor. The limit switches, once pressed, restrict the door from moving further. This way, the movement of the door is controlled. Figure 3 shows the concept generated in the CAD environment and Fig. 4 shows the final setup of the resource bin.

When a given batch of raw materials is received from inventory at the shop floor, the batch consists of a barcode that must be scanned before starting the in-process work. The information on the barcode includes material types and properties. This

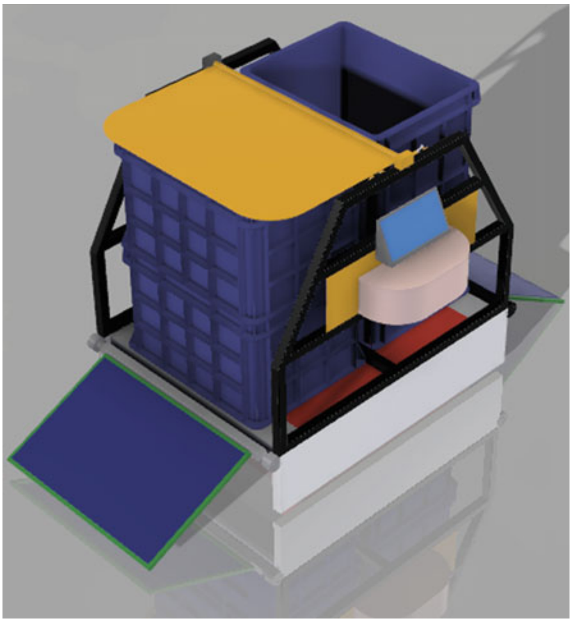

Fig. 3 Concept design of the resource bin

Fig. 4 Smart multi-material resource bin setup

information is utilized to open the designated side of the weighing scale and making the other side of the bin inaccessible.

4.2 Architecture and Working

A 200 kg capacity load cell is fixed to the industrial weighing scale platform of 0.6 m × 0.6 m, which is then connected to the Node MCU with HX 711 ADC by an I2C communication protocol. As each material gets accumulated in the respective bin, the weight of the material and the material type are stored in the computer and displayed on the screen, so that the worker can monitor the activity.

Barcode scanner is connected to the Raspberry Pi which scans the details of the type of the incoming material at that manufacturing station. The data is visualized on a dashboard. The architectural block diagram of the smart resource bin is shown in Fig. 5.

The visualization dashboard is built on the Node-RED platform; the dashboard displays the details of the material type and provides virtual buttons for (changing) material selection, visualization of weights of the material, and flow of material over time as shown in Fig. 6. The MQTT protocol is used to communicate Node MCU and RPi 3, which makes the connectivity wireless.

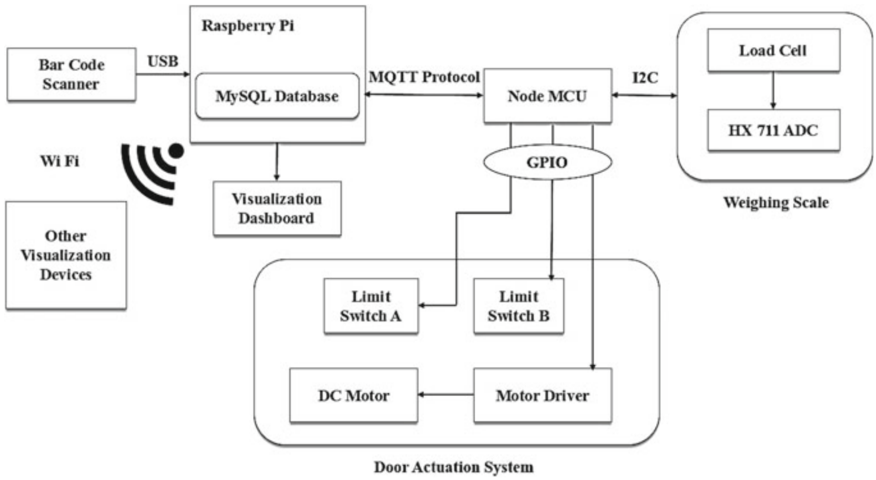

Fig. 5 Architectural setup and connectivity

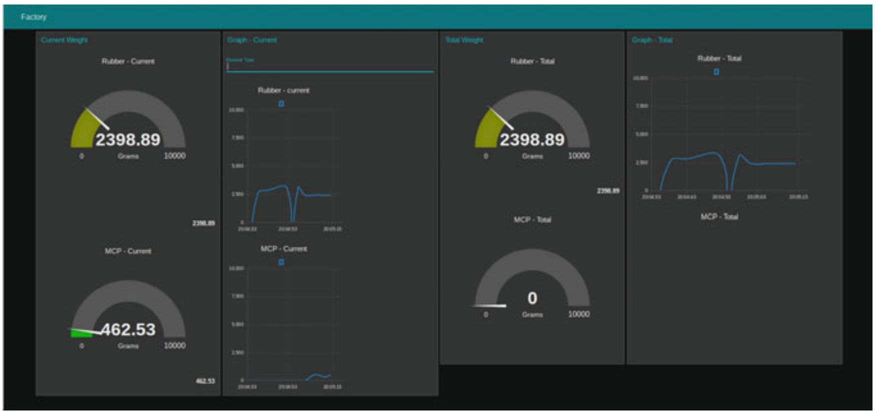

Fig. 6 Visualization dashboard

5 Execution

The smart multi-material resource bin was tested in the development environment for its performance by adding waste materials at different intervals of time, with the data stored in a local MySQL database, which could be retrieved in different file formats.

The dashboard displays information about the material type and its real-time weight and provides a graphical representation of the waste that is being continually dumped into the bin with appropriate timestamps. The above visualization is also possible to be provided on other devices, by connecting to a common Wi Fi network to which the RPi 3 is configured.

Using the system developed, a supervisor or top-level management can have real-time visualization of the waste generated at a manufacturing site and can remotely monitor the quantitative values of the waste. An email will be sent at the end of the shift/day to a top-level manager, which updates the wastes being collected.

5.1 Field Trial Observations

The smart multi-material resource bin has been successfully deployed at a live shop floor of the orthotic footwear manufacturing industry. During the field trial at the factory, we observed the following challenges which are being considered as feature enhancement in the upcoming version of the product.

Challenge I: The shop floor of the industry used two materials—rubber and Multi-Cellular Polymer (Chemically known as EVA) for the orthotic footwear design and they are cut at different work stations. The wastes from these stations are to be segregated and discarded individually but due to space constraints between these stations, the leftover materials were discarded at the same place and then manually segregated because of which there a mix up of materials was being discarded into wrong bins, which caused a misinterpretation of weights of materials being segregated.

Challenge II: The waste materials were supposed to be dropped inside the designated bin. The bins will be closed alternatively depending on the scanned barcode information. Once if the barcode is not scanned, even though with labeling on the bins the worker dropped the wrong material to the wrong bin. The post realization of the mistake made the worker scan the barcode and drop it again into the designated bin. This activity did not provide continuous data and it was difficult to identify the outlier.

Challenge III: There is regular power shut down in the factory, which interrupted the activities of the resource bin and the system needed a reboot. This also affected the analysis of the performance of the system, due to non-continuous data.

6 Conclusion

A smart multi-material tracking resource bin has been designed for meeting the challenges in MSMEs in Low and Medium income countries; it is intended to help track the quantity and type of materials being wasted. The historical data collected thus is then available for review. Integration into a Manufacturing Execution System (MES), and for performing data analytics, which should help in optimizing material usage and improving the efficiency of a manufacturing plant, resulting in revenue for the enterprise provided the operator is duly trained on the usage of the product, which we found to play a significant role in Industry 4.0.

The resource bin should help manufacturing enterprises at every stage of their operations for measuring and remotely monitoring waste, in the following manner:

- Tracking of the weight of the waste materials
- Segregation into reusable and non-reusable materials
- Tracking of the different types of material being used
- Data visualization and storage

We plan to deploy such smart multi-material resource bins at large scale manufacturing sites and test the performance in the near future with necessary upgrades. This should provide further insights into the sensitivity and reproducibility of the resource bin in the real-world applications, and their efficacy in supporting the reduction of waste and cost and improvement in productivity and sustainability.

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A Conceptual Model for Smart Manufacturing Systems

Ishaan Kaushal, L. Siddharth, and Amaresh Chakrabarti

Abstract Current manufacturing systems are incorporating digital extensions to meet the emerging trend of 'smart' manufacturing techniques. The underlying distinction of Smart Manufacturing Systems (SMS) is the digital network of several elements (machines, tools, auxiliary equipments, building services and people) that constitute these. The purpose of such a network is to enhance information transfer among these elements, as well as bolster the performance and efficiency of the roles that these elements are so entitled to. Such a network relies on the data collected from these elements; currently, both academicians and practitioners are delving into efficient ways to collect the data thus required. Although a plethora of models have been proposed for manufacturing systems, they seem to offer poor advice in regard to data collection from an overall system perspective. It is still not understood as to which elements should be focused and what are the efficient methods to collect data from these. To shed light on these gaps, we propose, herein, a new model for manufacturing systems, as illustrated by an orthotic shoe factory example.

Keywords CPS · IoT · Smart manufacturing systems

1 Introduction

There is a growing transition from conventional to Smart Manufacturing Systems (SMS), adding a digital dimension to these [1]. Much of this transition could be attributed to the accessibility of technologies such as the Internet of Things (IoT)

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A. Chakrabarti and M. Arora (eds.), *Industry 4.0 and Advanced Manufacturing*, Lecture Notes in Mechanical Engineering,
https://doi.org/10.1007/978-981-15-5689-0_8

and Cyber-Physical Systems (CPS). The underlying concept of IoT is to interconnect different elements of the universe using digital threads [2, 3]. CPSs are different from conventional ones in that, they couple digital and physical frontiers of a system, as well as interconnecting these. Such systems are known to be transparent, accessible, flexible and could be controlled and modified in real-time [4–6].

US Smart Manufacturing Leadership coalition define smart manufacturing as follows [7]:

> The application of advanced intelligence systems (CPS) to enable rapid manufacturing of new products, dynamic response to product demand and real-time optimization of manufacturing production and supply chain networks

SMSs examine and improve the processes, making these more value-oriented, responsive, flexible, lean, agile, productive (by monitoring the waste, downtime, etc.), energy-resource efficient, qualitative and transparent [1, 7, 8] such that the manufacturing system is profitable, safe and sustainable. For instance, Industry 4.0 [9], a German initiative, integrates almost all of the visible functional elements, right from production facilities to warehouses, also taking into account, the social angle embedded in these. Implementing such an SMS requires a workaround from three views [10].

1. Horizontal integration through value networks: Integration of organizations for an effective ecosystem
2. Vertical integration and networked manufacturing systems: Integration from the device level to enterprise level for flexibility, transparency and a fast decision-making
3. End-to-end digital integration of engineering. Integration across the value chain from design, to manufacturing, to supply chain and to customer requirements for mass customization and individualized products.

A digital network of elements constituting a manufacturing system is a means to attain flexibility or reconfigurability. The flexibility attribute is essential for batch production as well as for mass customization in response to customer demands [11]. Moreover, such a network of elements could help modify the system into being more efficient, safe, economically cheaper and environment-friendly [7, 12, 13]. The broad aim of this research is to model SMSs where the digital network adds a critical and influential dimension.

Systems are primarily classified as real and conceptual [14]. Similarly, an SMS has both real and conceptual elements that are connected via a network. The central element of the network is the cloud where the data is accumulated and processed. The data from the sensors embedded in physical elements are sent to the cloud, where it is examined in accordance with industry standards and the organizational objectives (economic, social and environmental). As a result of this assessment, feedback is given to the elements in different forms: engineering changes to products, instructions to humans, and alteration to process parameters, etc. Such a system could be self-contained, immunized to failures and less harmful to the environment.

In this multitude of processes, we narrow our focus down to the collection of data from physical elements. Keeping this focus in mind, we ask the following questions.

1. Which elements of a manufacturing system are exclusive and reliable sources of data?
2. How to map these sources and collect data from these?
3. How to organize these resources such that the computational load of the cloud is reduced?

In order to address the above, we conceptualize a model for an SMS and enlist the steps to develop the model so proposed.

2 Related Work

A manufacturing system is a collection of elements (machines, tools, material, people and information) that operate together within a physical boundary to produce a value-added physical, informational, or service product whose success and the cost is characterized by the measurable parameters of the system design [15]. Measuring the quality and performance of a manufacturing system requires examination of critical information at a specific physical resource level rather than at an abstract level [12]. Data collection, being the focus of our research, demands this level of granularity while modelling SMSs [16, 17].

It is important to question the relevance of data in terms of the decision-support it provides. Current means to obtain data fall short in this regard [17, 18]. There is a distinction between operational data and decision-making data; often these two do not concur, mainly due to the lack of generic database structures [19]. Moreover, there is a lack of analytic support to process huge volume and variety of data. These data-driven approaches tend to misfit with the existing conceptual models for manufacturing systems.

There are several means to classify manufacturing systems: advances in equipment, production layout (continuous and batch), production control (push, pull, or hybrid push/pull systems), inventory control (Engineer-to-order, make-to-order, make-to-forecast, make-to-stock) and production philosophy (lean, agile, le-agile). Several conceptual models are built over these classifications; some of these are Simulation-based, information-based, activity-based and factory-based, e.g. CMSD information model lists the entities and relationships that are essential to simulate manufacturing systems [20].

SIMA activity model distinguishes the hierarchy of process using the following convention: 'Ai: Name of the process.' For example, the main process 'A_0: Realize Product' it has four sub-processes: 'A_1: Design Product', 'A_2: Engineer Manufacture of Product', 'A_3: Engineer Production System' and 'A_4: Produce Product'. The model decomposes further to include inputs, outputs, controls and mechanisms of sub-processes [21]. Hubka's [22] model transforms material, energy and information using three kinds of systems (execution, information and management) that operate in active and reactive environments bounded by space and time.

Peripheral Model [23] divides a manufacturing system into three peripheral orders, which are clustered according to directly dependable subsystems placed on the first (e.g. direct energy and media supply for production machines), partly dependable subsystems located at the second (e.g. compressed air generation), and operating subsystems, which have no direct effect on the value creation process arranged on the third periphery (e.g. HVAC, lighting). Onion Layer Model [24] treats product processes as the core, surrounded by layers in the following order: machines, TBS infrastructure, decentral energy and mains supply. Hermann-Theide model [25, 26] is composed of three systems, whose input–output flows are elicited, taking into account the interdependencies between these. These systems are controlled using internal and external state variables.

The models reviewed above, are, in general, purpose-specific, domain-specific, or system-specific. None of these models seems to offer advice on potential modes and methods for data collection. In addition, these models do not consider the possibility of reconfiguring the elements of the manufacturing system using the data thus processed. In a nutshell, we aim to bridge the gap between manufacturing science and data science that are expected to go hand-in-hand in SMSs.

3 Proposed Model

3.1 Description

A manufacturing process is an interaction (material, energy, information transfer) between physical (machines, humans, conveyors, products) and information (control, management) entities in a controlled environment in a given time; it adds value to the materials that enter as inputs to these. Auxiliary processes such as material handling or transportation, although does not add value, but are essential to preserve the value of raw materials and improve overall performance of the system. Based on this, we propose a conceptual model of an SMS (Fig. 1).

The overall SMS is treated as an Input–Output black box. The inputs and outputs may fall under the following classes: Material Objects (MO), Energy (E), Information (I), Equipment (Eq), Human (H) and Environment (Env).

Several Objects (O_iS) constitute these inputs and outputs, also falling under one or more of these classes. These objects are characterized by one or attributes ($A_i^{'}s$); e.g. tiredness, tool-tip temperature, etc. Real-time assessment of these attributes could prove to be critically influential for the improvement of manufacturing systems for reasons mentioned earlier in Sect. 1.

These attributes are also direct indicators of what needs to be measured, from where and how these could be measured, addressing the first two questions raised

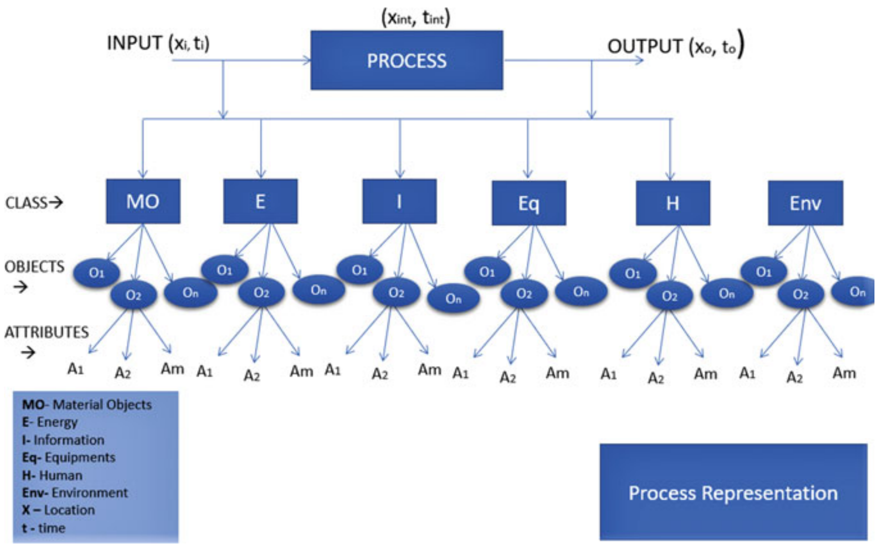

Fig. 1 Proposed conceptual model

at the end of Sect. 1. These attributes are essential ingredients for developing a digital network as these connect various objects using how one attribute affects its performance and of the others as illustrated using DSM (Fig. 2).

As an example, a set of attributes $\{A_1, A_2 \ldots A_6\}$ are organized in an extended form of Design Structure Matrix [27]. DSM, in addition to dependencies, can also be extended to represent information on attributes such as object identifiers, class identifiers and descriptions, as shown in Fig. 2a [28]. Focusing on the square portion

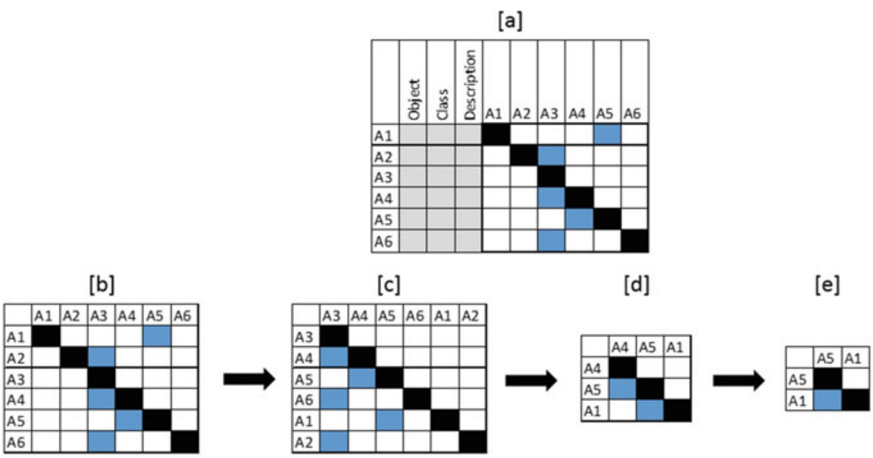

Fig. 2 Using DSM to structure dependencies among attributes

(Fig. 2b), the dependencies can be rearranged into the lower triangle (Fig. 2c) by interchanging rows and columns. Upon rearrangement, we understand that A_3 influences A_4, A_6 and A_1. Hence, we eliminate the rows and columns corresponding to A_6 and A_2 (Fig. 2d). We do not, however, eliminate A_4 because it influences A_5, which further influences $A1$ (Fig. 2e).

This way, the search can be narrowed to identify the dependent attributes. In this process, we understand that only A_3 needs to be physically measured; all other attributes can be identified using the network of relationships. Let us say, Quantity of manufactured goods (Q), Facility Utilization (U), Work in Progress (WIP) and Manufacturing Lead Time (T) are four attributes of the Production system. Looking at the mathematical models to observe any dependencies, we observe that Q influences the other three attributes (U, WIP, T). Therefore, Q is only needed to be physically measured while the other three attributes can be derived using Q. Using DSM as an analytic tool, we can strategically choose the exclusive (influencers, but not being influenced) attributes, to save time, cost and effort in measurement, addressing the third question raised at the end of Sect. 1.

These attributes distinguish our model from the existing ones, which are confined to the mere classification of the elements constituting a manufacturing system. In addition, these attributes are found at the finer most level granularity, which benefits the need for data collection to support SMSs, reinstating the point made earlier at the beginning of Sect. 2.

3.2 Guidelines

The overall steps to create the model are to identify the following: process, inputs–outputs,and environments—detailed below.

1. **Process**: The process could fall in one of the nine categories: Primary shaping, Forming, Separating, Joining, Coating/Finishing, Material Property change, Auxiliary Processes, Material Handling and Storage and Testing and Inspection [29–31].
2. **Inputs–outputs**: The identification of inputs and outputs conform to any of the following classes (See Fig. 1).

    a. *Material Objects (MO)* belong to seven classes: namely raw material, parts, sub-assemblies, assemblies, interface, consumables and residuals [32, 33]. The attributes to these MOs could be the following: name, type of material [34], number of parts, number of interfaces, type of interface, the life of consumables, type of consumables, amount of freshwater used, type of residuals, disposal, State, size, shape, colour, mass, features, quality, associated costs, associated environmental impacts and the previous process.
    b. *Equipment* belongs to the following classes: Machines, Hand tools, Material Handling, Storage and Software. The attributes to these include the following: Name, automation level, type, capacity, manning level, size/footprint, power

requirements, tool changes, maintenance schedules, precision, parameters, costs and environmental impact.

c. *Humans* associate the information about the task, duration, cycles, shift, equipment, failures, load grips, movements (involving a part of the body) and working conditions. These attributes are essential to monitoring their health and safety.
d. *Energy* can be classified as used energy and energy waste, which further can be classified according to the source of energy, type of energy, amount of energy, associated equipment, associated humans, energy wastes, load distribution, energy costs and environmental impact.
e. *Information* can be classified as input and feedback. The examples of input include the following: machine parameters, instructions and safety precautions to humans. Feedback is obtained from sensors as well as the processed information from the cloud and these are provided as modified attributes as that of inputs.

3. **Environment** can be classified as the immediate environment (inside the boundaries of a factory) and outside environment (outside the factory). Some of the attributes governing these environments include the following: temperature, humidity, noise levels and concentration of various gases. These attributes are crucial to measuring the environmental impact, which is one of the main goals of SMS.

3.3 Useful Criteria

While developing the model, there are some useful criteria to be kept in mind to have overall information about the complete factory (product, the interaction of processes, control strategies, auxiliaries and the system boundary)—detailed below.

1. **Type of product** obtained from ISIC [35] codes could serve as a basis for developing the model.
2. **Complexity** is an important criterion for modelling; complexity is characterized by the number of components and interactions constituting the product as a whole [29] [36].
3. **Building services** such as power requirements, maintenance schedules, resource requirements, capacity, operating procedures, overhauling procedures, condition monitoring, facility adjustments and facility retrofitting are important.
4. **Type of manufacturing system** like continuous vs batch production can be identified by observing the layout [37] (batch size, process flow, equipment, setups, process changes for new products), information and control (Production information requirements, raw material inventory and work in progress) of the system.

5. **Automation level** depends on the number and type of equipment and their manning level [29]; the levels of automation could be manual, semi-automated and highly-automated.
6. **Inventory control strategies** depend on storage requirements, demand and supply; these are classified as 'Engineer-to-order', 'Make-to-order', 'Make-to-forecast' and 'Make-to-stock'[38].
7. **Production control** involves predicting, planning and scheduling work; it requires information about routing, process tracking, machine load monitoring, inventory (parts, materials and in-process), purchasing, receiving, maintenance and quality. Based on production control manufacturing systems can be classified as a push, pull, or hybrid push/pull systems [39].
8. **Waste segregation and disposal** can be identified using residuals from each process, waste picking schedules, collection-segregation equipment, treatment procedure, power requirements for treatment/transportation, resource requirements.

From an overall perspective, we can obtain the type of manufacturing system, control strategies and related goals. From a deeper perspective, individual processes could provide information about material objects, equipment, energy, human, information and environment. Upon following the steps given in Sect. 3.2 and the criteria listed in this section, we should carefully choose the most relevant sources of data, pertaining to the goals of the organization.

4 Illustrative Example

As a case example, we model the manufacturing system of an orthotic shoe factory, which is geographically located closer to our institution. Prior to the identification of processes, inputs–outputs and environments as listed in Sect. 3.1, we examine several criteria as listed in Sect. 3.2 (See Fig. 3). It presents an eight-step guideline to map the factory level information by mapping the physical and conceptual elements of the system. Apart from gathering data from physical elements using sensors, sources like design files, factory observation, documentation and organization's strategies and goals are also equally important.

In accordance with the first step in Sect. 3.1, we identify the process by observing the operations at the factory. The process flow (See Fig. 4) presents complete information about the number and type of operations and network among them. The process flow of orthotic shoe factory presents a network of 16 different operations (from inventory to warehouse) required to make a product (shoe).

We detail the inputs/outputs (Fig. 5) for the process in accordance with the classes proposed in Fig. 1. This is a three-step mapping of process, input/output and environment. Figure 4 describes the Sole and heel cutting operation, which is one of the operations for shoe manufacturing and falls in the category of separating processes and the

- Step 1: Type of products manufactured [ISIC Codes]
  - ISIC Code - 1520 (Manufacture of footwear)
- Step 2: Complexity of Product and System
  - Complexity – 8 parts and 16 processes
- Step 3: Identify the Building services
  - Lighting
  - Fans and windows for air circulation and natural ventilation
- Step 4: General classification of manufacturing system
  - Identify the Production System : **Batch Production**
  - Layout of the system : **Process Layout**
- Step 5: Automation level
  - Non Automated
- Step 6: Mapping Inventory control strategies
  - Make to order
- Step 7: Production control
  - Pull System (uses Make to order strategy)
- Step 8: Waste Segregation and Disposal
  - Rubber is collected and sent for recycling
  - All other materials goes for disposal

Fig. 3 Criteria for the orthotic shoe manufacturer

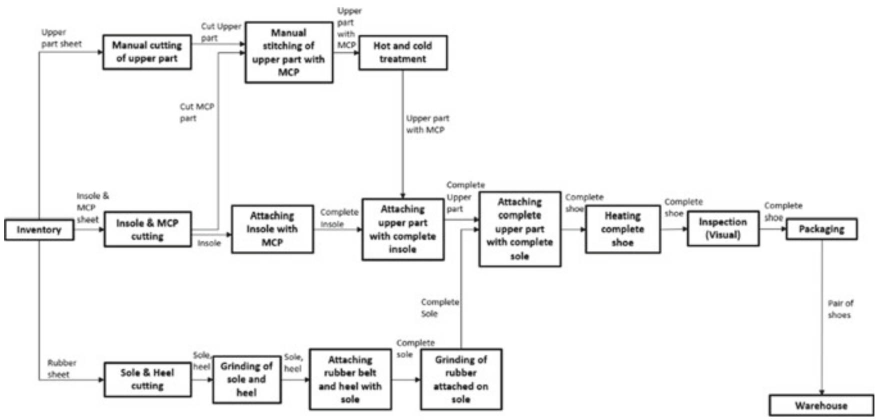

Fig. 4 Process flow of orthotic shoe factory

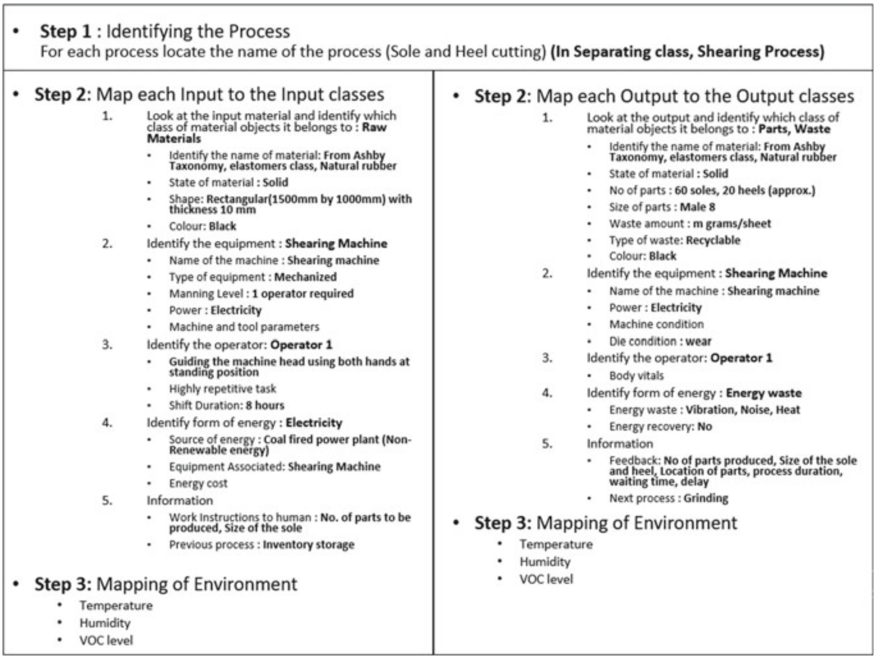

Fig. 5 Sole and heel cutting process description

process name is the shearing process (guided by Sect. 3.2). Similarly, inputs/outputs and environment are mapped as guided by Sect. 3.2.

5 Summary and Conclusions

The paper presents a model to identify the reliable sources of data by mapping the attributes of manufacturing processes, attributes of various input and output objects, attributes of the environment and the dependencies between these attributes. These attributes are direct indicators of what needs to be measured, from where and how these could be measured. Guidelines to map the individual processes, their inputs and outputs and environment are laid with useful criteria. The useful criteria helps in mapping the network of processes, auxiliaries, layout, manufacturing strategies, etc. and makes the model powerful enough to map the whole factory. From the useful criteria, goals of the organization can be identified, and based on those goals relevant data sources can be chosen. This will help by cutting down the effort in the collection and processing of redundant data.

6 Future Work

The model can be helpful in decision-making for instrumenting the factories based on enterprise goals. The model apart from mapping data at factory level can be extended to differentiate between confidential data and shareable data, for sharing among the suppliers and distributors. Data sharing is one of the roadblocks in sustainability assessment and creating a shareable data platform can help in accurately measuring the environmental, social and economic impacts of the product. Also, there is a limitation of the model, as it is striving to collect large quantity of data and generate huge information, it can be overwhelming for the decision-makers to make the correct decisions. Decision-making issues can be addressed by using techniques like Analytical hierarchy process (AHP) but needs further research.

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Digital Manufacturing

Casting Yield Improvement Using Modeling and Simulation Technique

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Abstract Yield is the ability of a foundry to manufacture acceptable casting in a cost effective manner. Improving yield offers many financial benefits to the foundry. Along with direct cost control, high yield is also associated with better quality and process control. By using computer simulation, an optimum gating system can be designed to improve the yield of the casting. This paper presents work on analysis of a real world industrial casting for yield improvement. A commercially available software AutoCast has been employed for this purpose. Further, the design of experiments (DoE) technique has been used to predict the significant factors and its effects on casting yield and rejection. The modifications suggested in this paper resulted in 0.42% improvement in yield at the box level. At the overall foundry level, 2.72% improvement in yield has been realized.

Keywords Computer simulation · Gating design · Yield · Quality

1 Introduction

Foundry industry is one of the oldest manufacturing industries. In the current scenario of global manufacturing, cost effectiveness and quality are crucial factors for survival of foundries. There is continuous pressure on foundries to supply castings at lower prices, shorter lead times with assured quality than ever before [1]. The profit of a foundry is greatly influenced by the casting yield, which in turn is defined as the total weight of good casting expressed as a percentage of the total weight of metallic material melted to produce them. Yield is a measure of foundry's ability to manufacture saleable castings in cost effective manner achieving the required quality. Achieving a balance between yield, defect free casting and manufacturing cost is always a challenge for foundries. Involvement of several parameters related to casting design (i.e. size, shape complexity, weight, and section thickness), material and process (molding material, feeding and gating methods, feed aids etc.) makes

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A. Chakrabarti and M. Arora (eds.), *Industry 4.0 and Advanced Manufacturing*, Lecture Notes in Mechanical Engineering,
https://doi.org/10.1007/978-981-15-5689-0_9

it a challenging problem. Due to complexity of the process, it is challenging to alleviate the defects (such as shrinkage porosity, blow holes, incomplete filling). Proper gating/feeding system design is critical to eliminate these defects as well as improve the casting yield. The quality of casting can be predicted by casting simulation, and if any defects are observed can be corrected by suitable modification in the gating and feeding system. Many researchers reported that, about 90% of the defects in castings are due to improper design of gating and feeding system, and only 10% due to manufacturing problems [2]. Thus, casting solidification simulation enables predicting and preventing potential problems in advance to achieve high yield at the desired quality level, and helps to develop the casting process in an optimal manner.

In the literature, various techniques such as design of experiments and casting simulation have been reported for defect analysis [3]. A large number of experimental investigations linking gating parameters with casting quality have been carried out by researchers and foundry engineers over the past few decades [4]. Several commercial tools (such as AutoCast, Z Cast etc.) have been developed to perform the casting simulation [5]. It has been reported that casting yield increased from 56 to 72% eliminating the defects [6]. Computer simulation minimizes the failure rate to a huge extent compared to manual trials [7]. The simulations were used to predict the temperature distributions and solidification sequences in the casting to optimize the casting conditions [8]. Casting simulation has become a powerful tool to visualize mould filling, solidification and cooling, and to predict the location of internal defects such as shrinkage porosity, sand inclusions, and cold shuts [9]. Iron foundries use these varieties of methods and software for design of feeding systems. The application of casting simulation software in the foundries not only minimizes the wastages of resources required for final castings, but also improves/enhances the quality and yield of castings, which implies higher value addition and lower production cost [10].

In many foundry industries casting simulation techniques are not used to investigate various defects and many times excessive shop floor trials are carried out which consumes the valuable resources. In the current work, the simulation and experimental investigations are carried out on real life industrial casting of 'Case Transmission' to improve the yield. AutoCast one of the commercially available simulation software has been used for this purpose because of its availability and proven ability. The AutoCast comprises a suite of nine programs to perform various tasks associated with casting design. Each program comprises a set of modules for design, solid modeling, simulation, analysis and improvement [11]. As a part of this study, existing process of manufacturing casting has been studied and few modifications have been done in gating design for improving casting yield and quality. The influence of key process parameters on yield and quality (rejections) have been studied using Taguchi Techniques. Further, new gating system is proposed. The results of simulation have been validated through shop floor trials. In the next section, importance of yield has been explained. In the subsequent sections, overall methodology, results of experimentation and modifications done are explained in details.

2 Importance of Yield

As mentioned earlier, yield is defined as the total weight of good, saleable castings expressed as a percentage of the total weight of metallic materials melted to produce them. It can be represented as,

$$\text{Yield} = \frac{\text{Total weight of good castings}}{\text{Totalweight of metal melted}} \times 100$$

Actual yield of a foundry is always less than 100% because weight of the metal melted always exceeds that of the good quality castings dispatched. Other than material saving, improvement in yield also helps to reduce the costs associated with melting the metal (energy cost).

3 Methodology

The overall methodology for the current work is depicted in Fig. 1. The main steps in the current approach are:

1. Study the existing process and method
2. Simulation for existing method
3. Design of Experiments (DoE) and shop floortrials
4. Design modifications and shop floor validation

These steps are explained in next subsections.

3.1 Study of Existing Process

As mentioned earlier, Case Transmission Casting has been selected for yield improvement (please refer Fig. 2). The data pertaining to manufacturing the casting has been

STEP 1	STEP 2	STEP 3	STEP 4
<u>Study of existing process</u> -Part model -Material -Process parameters -Methods design -Existing defects	<u>Simulation for existing method</u> -Parting lines -Cores -Feeders -Feedaids -Gating system -Mould cavity layout	<u>DoE and shop floor trials</u> -Selection of critical parameters -Analysis of results -Shop floor trials	<u>Design modifications and shop floor validation</u> -Modification in existing design -Simulation and analysis of modified design(step 2 is repeated) -Shop floor varification

Fig. 1 Overall methodology

Fig. 2 Case transmission casting

Table 1 Component and process details

Grade of metal: FG 220	Unit weight of casting: 61 kg
Height of casting (C): 375 mm	Sand material: green sand
Pouring temperature (T_p): 1430 °C	Feeding time: 15 s
Liquidus temperature: 1250 °C	Solidus temperature: 1154 °C
Density of metal: 7200 kg/m^3	Total weight of casting in mould box: 61 * 2 = 122
Total dimensions of the mould box: 1200 mm × 800 mm × 725 mm	Type of gating system used: hybrid gating system
Shape of mould box: rectangular	Mould layout: 2 castings per mould

collected from the shop floor. Main parameters related to casting manufacturing are shown in Table 1.

The feeding and gating design for existing method have also been studied and analysed in detail. The results of simulation for existing method are discussed in brief in the next subsection.

3.2 Simulation Results for Existing Method

With the help of relevant information, the simulation trial was taken in order to analyse the defect for the existing gating system. In the existing system, a central sprue was used to feed both the cavities of two cavity mould. The pouring was done through a sprue which was connected to the runner. The runner was connected to mould by means of ingates (Fig. 3b). The results of simulation, especially for the defects related to solidification and blow holes are shown in Fig. 3c, d.

The simulation result shows that, the hot spot is absorbed in the sprue cup and there is almost no shrinkage porosity in casting. However, blow holes have been predicted at the corner of castings (encircled in Fig. 4d). The results were verified with the real castings manufactured by the foundry. It was verified that, indeed there was a significant rejection (5–8%) because of blow holes in the foundry at the predicted location. The box yield with the existing design was 81.33%.

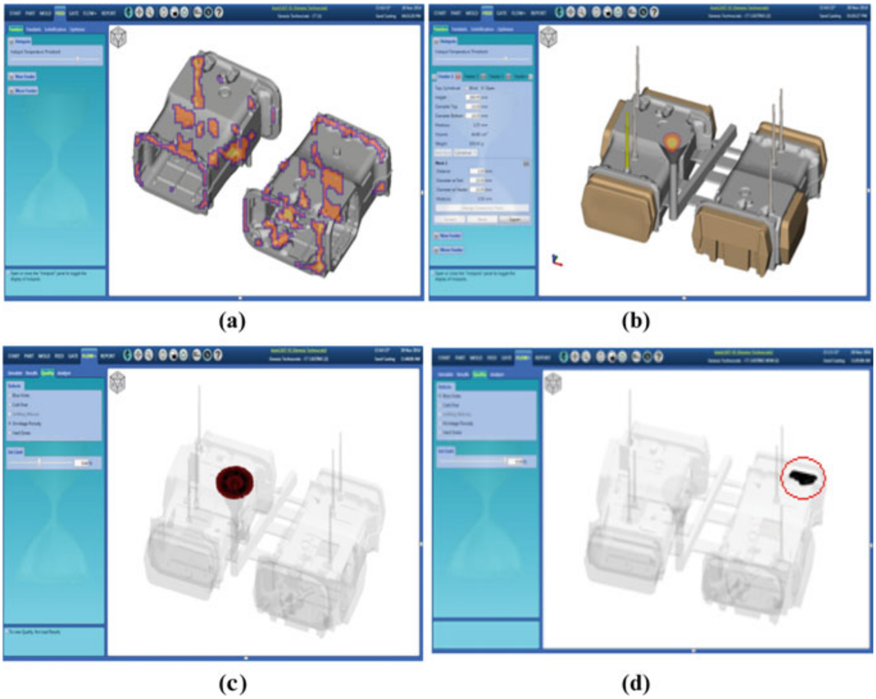

Fig. 3 Simulation results for existing system, **a** massive section shows chances of hot spot, **b** hot spot absorbed in sprue cup, **c** shrinkage porosity absorbed in sprue cup, **d** prediction of blow holes

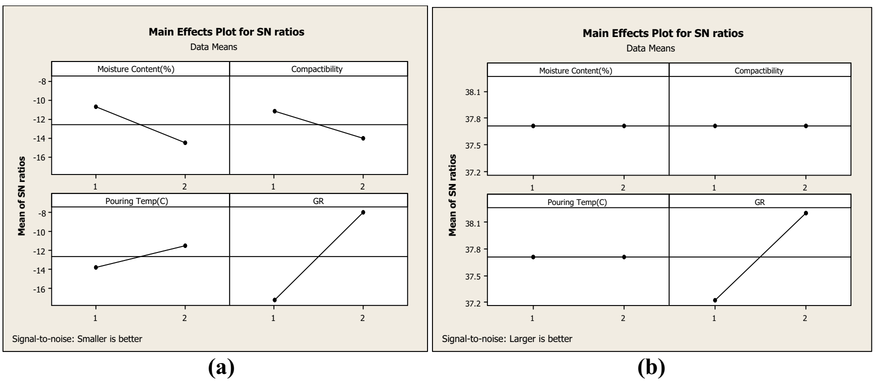

Fig. 4 **a** S/N main effects plot for % rejection, **b** S/N main effects plot for box yield

Further investigations were performed to improve the box yield and reduce the defects related to blow holes.

3.3 Modification in Gating Design and Results

Several experiments were conducted to study the effect of important parameters (pouring temperature, moisture content, compactibility and gating ratio) on yield and quality. The principles of Taguchi method were applied for conducting these experiments [12]. L8 array has been used for experimentation. Based on discussions with domain experts, various levels of these parameters have been selected. These levels are shown in Table 2. For each of the simulation run, the value of box yield, and potential defect have been predicted through software. In addition, shop floor trials were taken to determine rejections pertaining to these modifications. The data collected from these experiments is shown in Table 3. Collected data have been analyzed using Taguchi method. Taguchi method uses signal to noise ratio in order to convert the trial result data into a value for the optimum setting analysis [12]. The signal to noise ratio (SN) ratio main effect plots for various response variables are shown in Fig. 4. Minitab16 software has been used to study the influence of various parameters on yield and rejections [13]. With the available data set maximum box yield 81.33% can be achieved with minimum reduction of 1.13%. In the contest of

Table 2 Factors and levels

Process parameter	Level 1	Level 2
Moisture content (%)	3.2–3.5	3.5–3.8
Compactibility	38–40	40–42
Pouring temperature (°C)	1415–1425	1435–1445
Gating ratio	1:2:1.5	1:1.6:0.8

Table 3 Standard L8 array for % rejection and yield along with S/N ratio values

Moisture	Compactibility	Pouring temperature	Gating ratio	% Rejection	Yield	SNRA1	SNRA2
1	1	1	1	7.95	72.61	−18.0073	37.2199
1	1	2	2	1.13	81.33	−1.0616	38.2050
1	2	1	2	2.27	81.33	−7.1205	38.2050
1	2	2	1	6.81	72.61	−16.6629	37.2199
2	1	1	2	3.40	81.33	−10.6296	38.2050
2	1	2	1	5.68	72.61	−15.0870	37.2199
2	2	1	1	9.09	72.61	−19.1713	37.2199
2	2	2	2	4.54	81.33	−13.1411	38.2050

the null hypothesis of equality of several means of normal populations having same variances, the analysis of variance technique can be used. SNRA1 and SNRA2 are the mean and variance respectively for the given set of data.

As evident from the analysis, within the selected range, the most influencing parameter on rejection is the gating ratio, which accounts for (76.20%) of the total effect. All other parameters such as moisture content, compactibility and pouring temperature are less significant parameters. From SN ratio plots, it is clear that percentage rejection and box yield are minimum and maximum respectively at second level (1:1.6:0.8) of gating ratio, first level (3.2–3.5) of moisture content, first level (38-40) of compactibility and second level (1435–1445) of pouring temperature. Based on the above analysis, simulation results, inputs from domain experts and some practical constraints from foundry, following improvement were proposed for yield and quality improvement:

- Runner bar modification: The height of the runner bar is reduced by 6 mm as shown in Fig. 5. This resulted into 0.74 kg mass reduction.
- Addition of vent (encircled in Fig. 6a) for escaping the gases and prevent the blow holes (encircled in Fig. 6d).

The simulation study was carried out with these improvements. The results of this study are shown in Fig. 6. As evident from the figure, with proposed modifications the defects related to blow holes have been eliminated. In addition, decrease in runner bar size resulted in 0.42% improvement in box yield i.e. 0.74 kg saving of material. With this method, trials were performed in shop floor and realized that defects pertaining to blow holes have been reduced to 1.5%. This reduction in defects also contributed

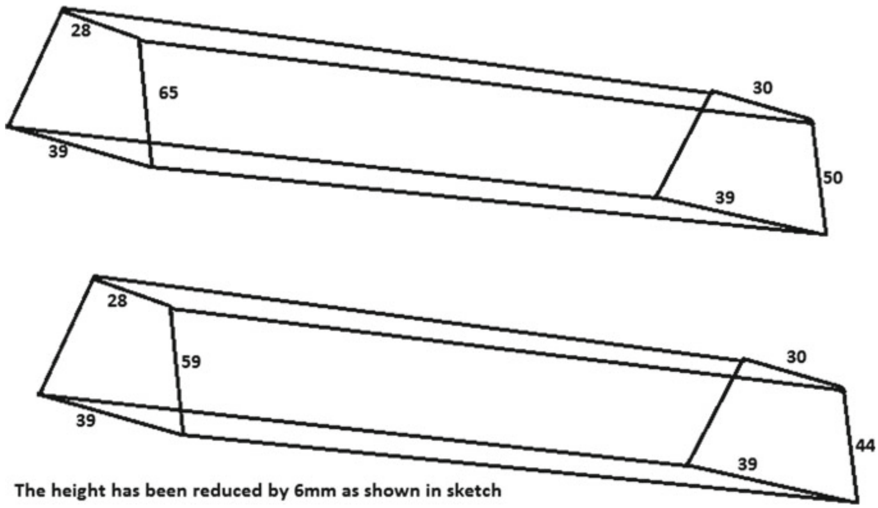

Fig. 5 Change in the height of runner bar

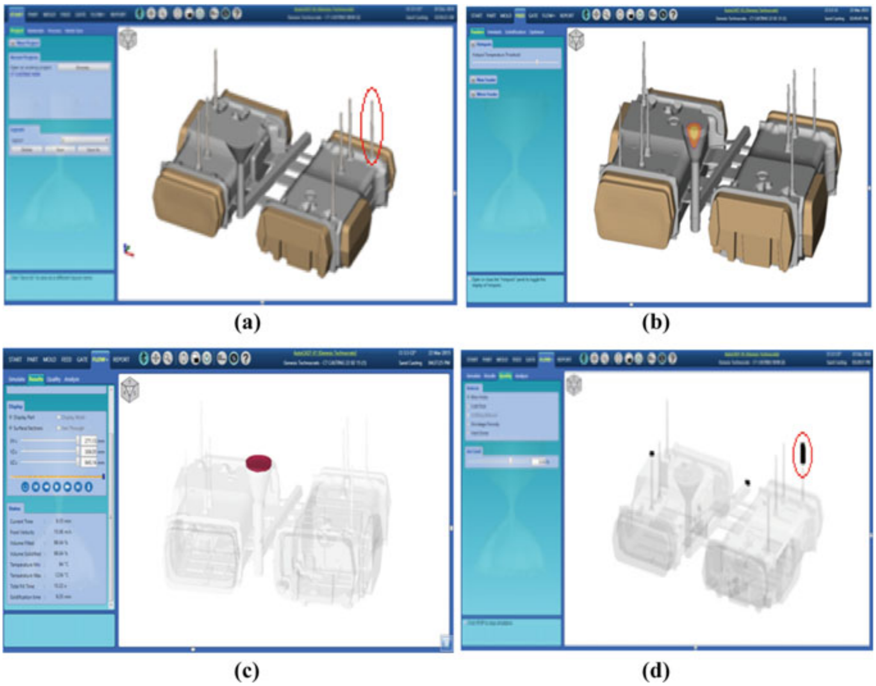

Fig. 6 Simulation results for modified system, **a** introducing additional flow off pin, **b** hot spot absorbed in sprue cup, **c** shrinkage porosity absorbed in sprue cup, **d** elimination of blow holes by flow off pin

to improvement in overall foundry yield. Thus, 2.72% overall yield improvement has been observed in the foundry.

4 Conclusions

In this paper, an application of a simulation software program for mold filling, solidification analysis and yield improvement has been presented. The simulation program has been used to identify critical locations, filling pattern and solidification related problem areas in the casting. Based on the analysis of simulation and experimental results modifications in the gating system have been performed. These modifications resulted in 0.42% improvement in yield at box level and 2.72% improvement in yield at overall foundry level. The higher improvement in yield at foundry level was realized because of reduction in rejection percentage. A significant benefits and savings have been realized by the foundryas the number of casting manufactured per day is in large quantity. These include savings in the costs associated with in metal, time, labor and energy. Further, experimental investigations were carried out to study the influence of various parameters on yield and quality, and analysis was done using Taguchi techniques. For the selected parameter levels, it was realized that percentage rejection and box yield are minimum and maximum at second level (1:1.6:0.8) of gating ratio, first level (3.2–3.5) of moisture content, first level (38-40) of compactibility and second level (1435–1445) of pouring temperature. In this work, shop floor trial runs results are validated by means of casting simulation results demonstrating the use of casting simulation technique in case of real life cases to address casting defects of blow holes maintaining the better yield of 81.33%. The yield improvement of 0.42% sounds small but as the number of casting manufactured per day is in large quantity, it leads to be very effective saving the costly aluminum metal of 0.74 kg at box level.

Acknowledgements The author would like to express appreciation for the support from Ghatge Patil Industries. Authors appreciate the great help from Mr. Milind Bhave (Vice President, Foundry Division, Ghatge Patil Industries) for his professional suggestions on research work. My deepest gratitude goes to Mr. Sanjay Mali of Genesis Technocrats.

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Comparison of Two Different Simulation Methods for the Finite Element Analysis of Electromagnetic Forming and Perforation (EMFP) of Tubes

Sagar Pawar, Dinesh Ray, Sachin D. Kore, and Arup Nandy

Abstract The electromagnetic forming and perforation is a high strain rate dynamic process, carried out within microseconds, and it is difficult to measure the material behavior experimentally; hence, FEA is used. This paper presents the comparison of non-coupled and coupled simulation approach. In non-coupled simulations, using EM fields obtained in Ansys Maxwell, transient magnetic pressure is calculated, and it is used as an input load in the mechanical model. In coupled simulations, structural deformation due to initial Lorentz force is accounted for adjustment of the calculation of electromagnetic fields. This modified EM fields again change the structural deformation. These iterations continue until sufficient convergence is achieved. Thus, in coupled model, mutual dependence between EM fields and structural deformation is considered which is missing in non-coupled simulation. The numerical results are compared with the experimental results, and overall, the coupled simulation results are found to be in good agreement with experimental results.

Keywords Electromagnetic forming · Coupled simulations · Finite element methods · Perforation

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A. Chakrabarti and M. Arora (eds.), *Industry 4.0 and Advanced Manufacturing*, Lecture Notes in Mechanical Engineering,
https://doi.org/10.1007/978-981-15-5689-0_10

1 Introduction

The electromagnetic forming is a magnetic pulse forming process which uses magnetic forces for structural deformation [1]. In EM forming, the magnetic forces replace the punch to get the desired shape [2]. The coil position decides the type of process; for the compression of the tube, the coil is placed inside the tube [3], and for expansion, the tube is placed inside the coil [4].

Electromagnetic forming and perforation (EMFP) of the tube is an application of EM forming process, where simultaneous expansion and perforation of the tube can be possible. EMFP can have applications in oil and gas industries and automobile industries where deformed perforated tubes are used. The schematic representation of the electromagnetic forming process is shown in Fig. 1a. A capacitor bank is charged by a short duration of time, and the stored energy is discharged through the coil. Upon the discharging the capacitor bank through the coil, it generates the magnetic field around the coil which induces the current (I_w) in the conductive tube. The induced current generates another magnetic field, and the interaction of two magnetic fields results in the Lorentz forces which deform the tube plastically. I_w, L_w and R_w are the induced current, inductance of workpiece (tube) and resistance of the workpiece. Punches are fixed on the die; during expansion, the tube gets perforated through the punches as shown in Fig. 1b. C_{in} and C_{out} represent the current in and out ends. Tube before and after the experiment is shown in Fig. 1b.

The large amount of finite element analysis work has been done on EM forming of the tube [5]. Different algorithms are used for the simulation. In the case of coupled simulations, EM fields have been computed, and Lorentz force is evaluated at each node of the element and added to the mechanical solver. The mechanical solver deforms the workpiece, and at the same time, the geometry of the electromagnetic model is updated; this cycle repeats all the time [6–8, 10]. For the electromagnetic compression of tubes, non-coupled simulation models were developed where electromagnetic analysis software is used for the calculation of the magnetic field

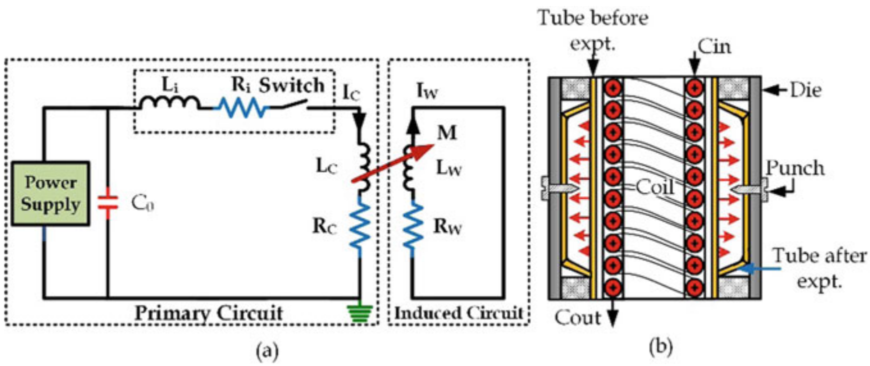

Fig. 1 **a** Schematics representation of EM forming process, **b** perforation of the tube

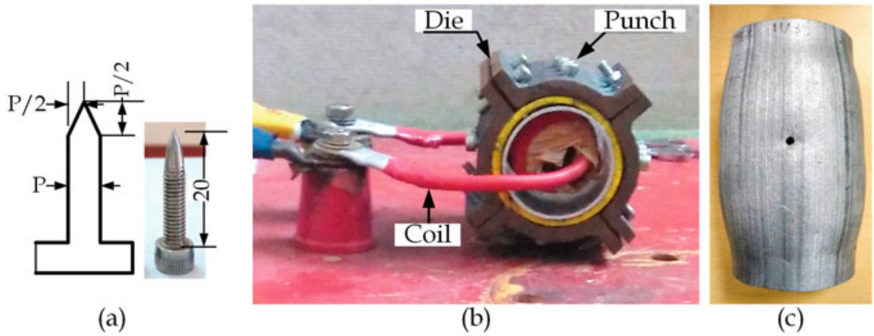

Fig. 2 **a** Pointed punch, **b** experimental setup and **c** tube after the experiment

and mechanical analysis software is used for structural deformation [11–13]. The non-coupled approach overestimated the deformation as compared to the coupled approach [9]. The detailed literature survey shows that the comparative study of two different simulation algorithms for finite element analysis of EMFP is not studied. Here, in this study, both non-coupled and coupled simulation models are developed for finite element analysis of EM perforation of the tube. The results obtained from the simulations are validated with experimental results.

2 Experiments

The electromagnetic perforation setup consists of aluminum tube, coil, pointed punch and die. Here, the tube is a workpiece, and the coil is used as a tool. The experimental setup and tube after the experiment are shown in Fig. 2.

Experiments are carried out on aluminum 6061 tubes having 1 mm thickness, 50 mm diameter and 100 mm length at various discharge energies. Punches made of SS-302 are used for the perforation. The coil made of 16 mm^2 Cu cable having 100 mm length is used for the experiment. The coil is placed inside the tube; it covers the total length of the tube. At 6.2 kJ discharge energy, perforation is possible. The results obtained from this experiment are used for the validation of simulation models.

3 Simulation Models

In this study, both non-coupled and coupled simulation models are developed for finite element analysis of EM perforation of the tube. The flowchart of both the model is shown in Fig. 3.

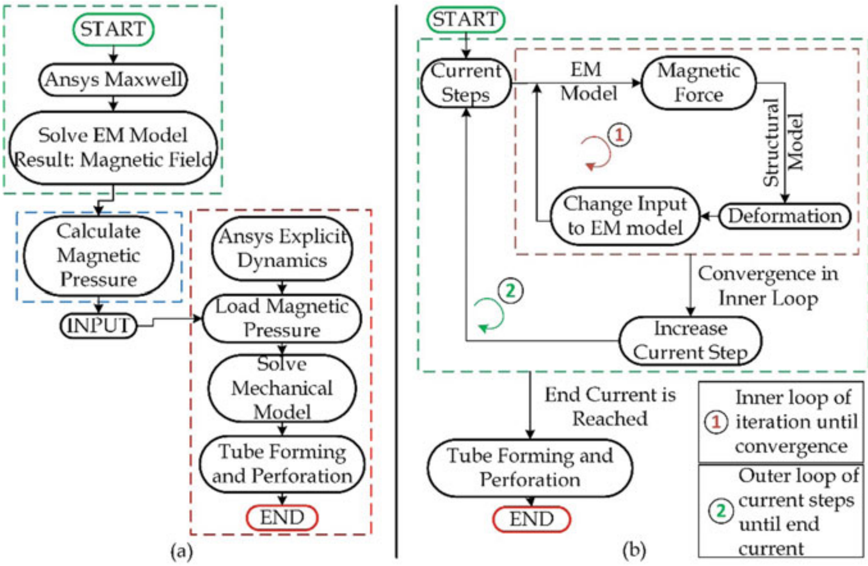

Fig. 3 Flowchart for **a** non-coupled and **b** coupled simulations

The non-coupled approach can be used for the good approximation of the perforation process. The coupled approach used here has limitations like the use of mesh type and mesh method; to overcome these limitations, non-coupled approach can be used [10]. Al 6061 material is used for the tube. The material properties used are given in Table 1. Material properties of Cu alloy are used for the coil in coupled simulations. The properties of Cu alloy are given in Table 1. In both the simulations, die and punch are made rigid and fixed in all directions. SS 304 is used for punch and die, and material properties used are given in Table 1.

To simulate the material behavior at high strain rate, Johnson-Cook material and failure models are used for the tube. The constitution equation of the Johnson-Cook

Table 1 Material properties [14]

Material property		Al 6061	Cu	SS 304	Unit
Density	ρ	2700	8940	7800	kg/m^3
Modulus of rigidity	G	26	45	210	GPa
Modulus of elasticity	E	68.9	97		GPa
Poisson's ratio	γ	0.33	0.31	0.3	
Heat capacity	C	896	3.935	423	J/kg K
Thermal conductivity	k	126	391	14	W/m K
Electrical conductivity	σ	25	58	1.4	MS/m
Melting temperature	T_m	925	1355		K

Table 2 Johnson-Cook strength model parameters [14]

Parameter	A (MPa)	B (MPa)	C	n	m	T_m (K)	$\dot{\varepsilon}$ (s^{-1})
Value	324	114	0.002	0.42	1.34	925	1

Table 3 Damage constants used in the Johnson-Cook failure model [14]

D_1	D_2	D_3	D_4	D_5	T_m	$\dot{\varepsilon}$
−0.77	1.45	0.47	0	1.6	650	1

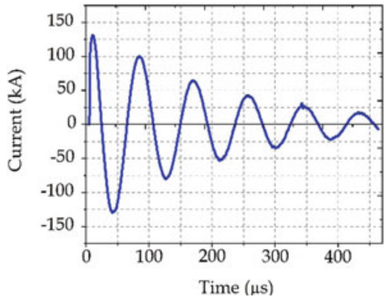

Fig. 4 Current curve obtained at 6.2 kJ discharge energy

material model is given by Eq. 1, and values of constants are given in Table 2. The constitutive equation of the Johnson-Cook failure model is given by Eq. 2. The values of damage constants are given in Table 3.

$$\sigma_y = \left(A + B\bar{\varepsilon}^{p^n}\right)\left(1 + c\ln\dot{\varepsilon}^*\right)\left(1 - \left(\frac{T - T_R}{T_m - T_R}\right)^m\right) \quad (1)$$

$$\varepsilon_f = (D_1 + D_2 \exp\left(D_3\left(\frac{P}{\sigma_y}\right)\right)(1 + D_4 \mathrm{Ln}\dot{\varepsilon})\left(1 + D_5 T^*\right) \quad (2)$$

The current waveform obtained from the oscilloscope during the experiment is used as input to Ansys Maxwell and LS-Dyna™. Figure 4 shows the current waveform obtained at 6.2 kJ discharge energy. The maximum current obtained is 132 kA.

3.1 Non-coupled Simulations

In the non-coupled simulation approach as shown in Fig. 3a, two simulation softwares, namely Ansys Maxwell and Ansys Explicit Dynamics, are used. The objective of simulation in Ansys Maxwell is to determine the electromagnetic field intensity around the coil when a high electric current passes through it. The current curve

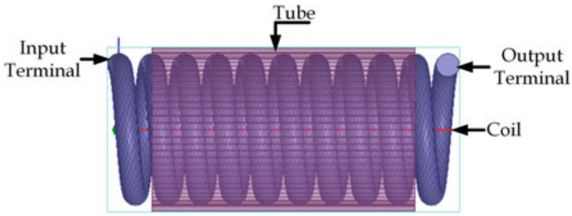

Fig. 5 Ansys Maxwell setup

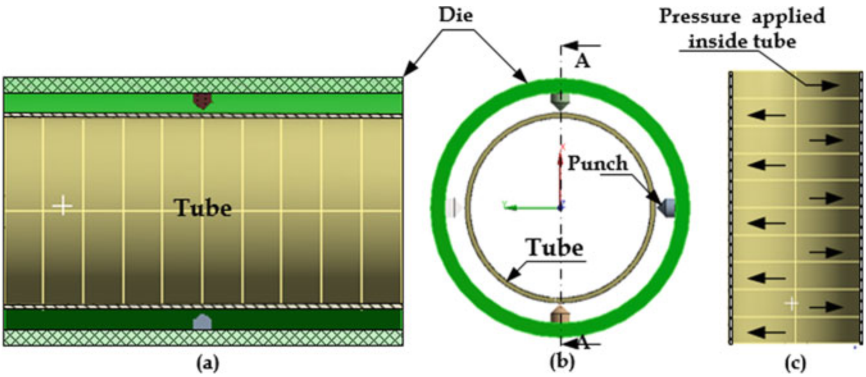

Fig. 6 **a** Cross-sectional view, **b** front view and **c** pressure application on inside tube surface (cross section of the tube)

obtained from the oscilloscope during simulation is used as input. Figure 5 shows the coil–tube setup used in Ansys Maxwell. The magnetic field intensity (H) is obtained around the coil with respect to the conductive tube.

The 3D model used for this structural deformation is shown in Fig. 6. The obtained transient magnetic pressure is used as input for structural deformation in Ansys Explicit Dynamics. This pressure is applied inside the tube as shown in Fig. 6c. The mesh convergence study is done, and optimum mesh and time steps are used for simulation. The mix triangular and quadrilateral elements are used for the meshing of the tube; the size of the element is 0.001 m. Adaptive mesh refinement method is used for minimizing the distortion of mesh due to large deformation. Die is fixed in all the directions.

3.2 *Coupled Simulations*

Coupled electromagnetic and mechanical simulation is carried out in LS-DYNA. The flowchart of the process is shown in Fig. 3b. Here, at every time step, the Lorentz forces are calculated at each node and automatically transferred as input load to the

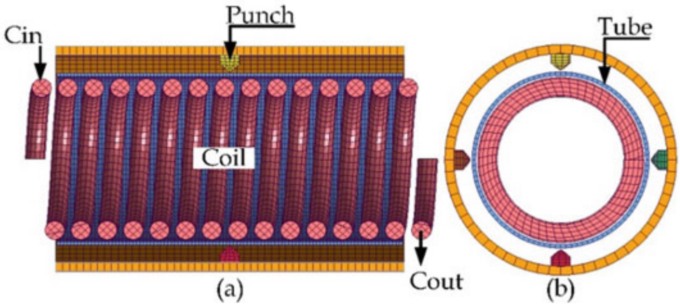

Fig. 7 EM perforation model in coupled simulation **a** cross-sectional view and **b** front view

mechanical model. Mechanical solver deforms the tube, and the deformed geometry modifies the electromagnetic field which further affects the structural deformation, and these iterations continue until convergence is achieved. The 3D model used for this simulation is shown in Fig. 7. This model consists of tube, coil, punch and die. The current input (C_{in}) and output (C_{out}) segments are created at the coil end as shown in Fig. 7a. The current waveform obtained from the oscilloscope is directly applied through these segments. The quadrilateral elements are used for meshing all the parts. Mesh convergence study is done, and the optimum mesh size is used for simulation.

4 Result and Discussion

As electromagnetic perforation takes place within microseconds, so it is very difficult to find out some parameters experimentally. The magnetic field, radial displacement, cross section of the hole and effective plastic strain are obtained numerically and compared. The simulations are carried out and validated with the experiment results.

Figure 8 shows the variation of generated magnetic pressure with time for coupled and non-coupled simulations. It is observed that the magnetic pressure generated in the non-coupled simulation is more as compared to the magnetic pressure generated in the coupled simulation. Magnetic pressure in case of the coupled solver is calculated by Eq. 3. [2], where the loss in magnetic field lines because of diffused magnetic flux lines due to structural deformation is considered.

$$P(r,t) = \int_{r_0}^{r_i} F(r,t) = \frac{1}{2}\mu(H_{\text{gap}}^2(t) - H_{\text{diffuse}}^2(t)) \tag{3}$$

In the case of non-coupled modeling, the magnetic field is calculated only on the inner surface of the tube and diffused magnetic flux lines are neglected. Thus, the loss in the magnetic field due to diffused magnetic flux is neglected. Due to this,

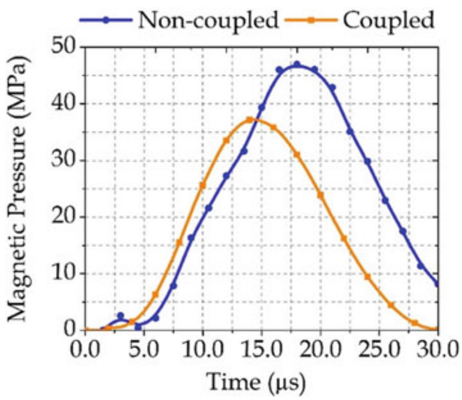

Fig. 8 Variation of magnetic pressure with time

the magnetic pressure obtained in non-coupled modeling is more than the coupled modeling. An analytical formula used for calculation of magnetic pressure is given by Eq. 4.

$$P(r,t) = \frac{1}{2}\mu H_{\text{gap}}^2 \tag{4}$$

The non-coupled approach leads to an overestimation of the final deformation profile as shown in Fig. 9. The radial displacement obtained in the coupled simulation is closed to the experimental results. Almost 94% agreement with the experimental result observed in case of coupled simulations. The overestimation in the non-coupled simulation is because of the higher magnetic pressure, which is the result of an overestimation of the total magnetic field intensity.

The cross sections obtained in both simulation approaches are compared with experimental results. Figure 10a shows the cross-sectional view of the model after simulations. In both simulation methods, all four holes get perforated. In both the simulation approach with a pointed punch, the petaling phenomenon is observed.

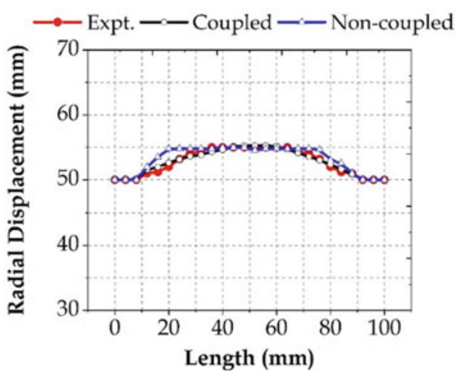

Fig. 9 Radial displacement of the tube

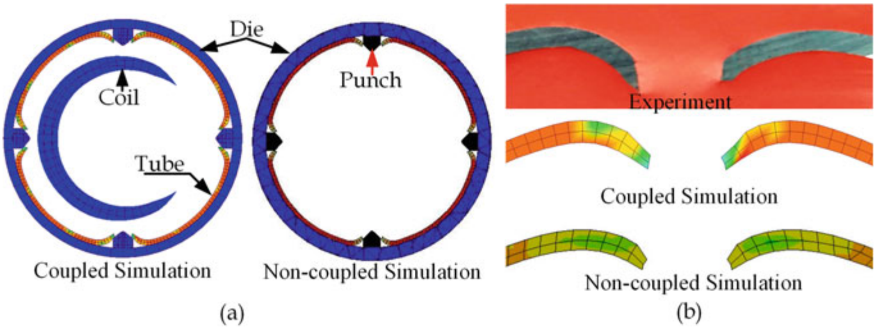

Fig. 10 **a** Cross-sectional views of the perforated tube and **b** cross sections of perforated holes

The petaling obtained in simulations is the same as obtained in the experimental result. Figure 10b shows a comparison of the cross sections of perforated holes.

The cross sections are almost same, but as a consequence of higher magnetic pressure, the hole size in case of non-coupled simulation is more as compared to the experimental results, while the hole size obtained in the coupled simulation is closed to the experimental results. The diameter of the perforated holes obtained in experiment and simulations is given in Table 4.

Table 4 Diameter of the perforated hole

	Experimental	Coupled	Non-coupled
Diameter of perforated hole (mm)	4.5	4.65	5.2

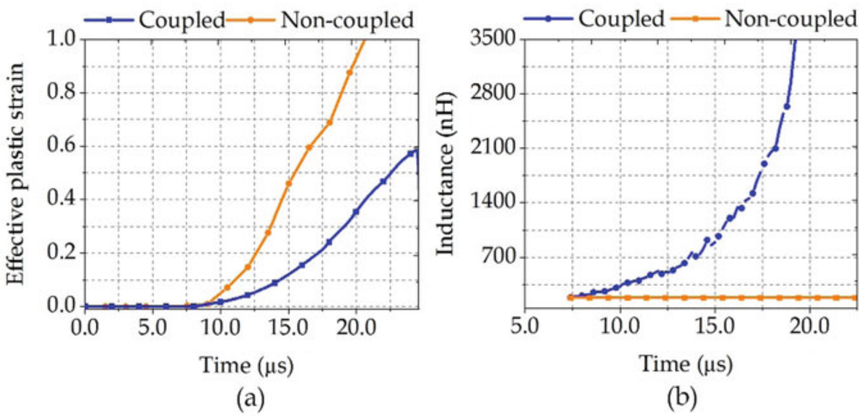

Fig. 11 **a** Variation of effective plastic strain with time and **b** variation of inductance of FEM model with time

The variation of effective plastic strain with time is shown in Fig. 11a. As a result of more magnetic pressure, the effective plastic strain developed in the non-coupled simulation is more than the coupled simulation and the variation increases with time.

Figure 11b shows the variation of the total inductance of FEM model with time for both simulation methods. In case of coupled simulation, after the deformation the geometry is updated each time in the electromagnetic solver, hence, the gap between the coil and tube increases which require more magnetic field energy (E_{field}) to deform the workpiece and that leads to higher inductance values (L_{FEM}). The inductance of the developed FEM model is calculated by Eq. 5,

$$E_{\text{field}} = \frac{L_{\text{FEM}}}{2} I^2 \tag{5}$$

In the non-coupled approach, the inductance of FEM model is calculated at only maximum and minimum current values which results in constant inductance for all instances of time.

5 Conclusion

i. As a result of excessive magnetic field generation, the magnetic pressure obtained in non-coupled simulation is more which results in the overestimation of deformation. On the other hand, in case of coupled simulations, the deformation obtained is almost 94% agreement with the experimental result.
ii. In both the simulation approaches, the petaling is observed which is the same as that of obtained in experimental result, but in comparison with the diameter of the perforated hole obtained, coupled simulation is more accurate.
iii. The variation of effective plastic strain with time obtained in the non-coupled simulation is more as compared to the coupled simulation. This is because of the more pressure application in non-coupled simulations.
iv. The total inductance of model in case of coupled simulations is increasing with time because of the increased gap between tube and coil after each time step, while in non-coupled simulation, only maximum and minimum values of current are used for the calculation of inductance of the model which results in constant inductance with a time.
v. The deviation between the two approaches increases with time, and non-coupled approach overestimates the results. The non-coupled approach can be used for the good approximation of perforation process, and also, some limitations of coupled approach can be overcome by the use of different mesh types and meshing methods; otherwise, for more accurate estimation of results, the coupled approach should be used.

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Impact of Digital Manufacturing in Industrial Transformation

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Abstract In recent years, the influence of digital manufacturing technologies has grown rapidly so as to reduce the product development time and cost alongside addressing the customization, improving the product quality and reducing the time to market. Digital manufacturing which integrates digital and manufacturing innovations and advancements enable the industries to engineer the products in preferred style and helps in meeting the demand within a short time compared to conventional methods. It helps in defining the manufacturing processes and process information concurrently using digital product data during the product design stage itself. It is an integrated approach consisting of manufacturing simulation, visualization, ergonomic and human factor analyses, overall view of product and process design which enables us to check the product design changes subjected to the process constraints and capabilities during the design stage itself. In this paper, the necessity and the traction for the adoption of digital manufacturing are discussed.

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A. Chakrabarti and M. Arora (eds.), *Industry 4.0 and Advanced Manufacturing*, Lecture Notes in Mechanical Engineering,
https://doi.org/10.1007/978-981-15-5689-0_11

Keyword Digital manufacturing · Process simulation · Ergonomics · Cycle time · Capacity calculations

1 Introduction

Manufacturing industry is trying to integrate design, manufacturing and product support processes to overcome the challenges being faced due to the increase in global competitiveness, dynamic market trends and varying customer requirements. Information technology has dramatically aided the traditional industry to overcome the barriers and help in dealing with ever-growing complexity in products and manufacturing processes without compromising in quality alongside reducing the product design and development time [1]. Rapid response to the business opportunity is the most important factor to get the edge over competitors. Digital manufacturing serves as a new paradigm in the manufacturing environment as shown in Fig. 1 to optimize the manufacturing processes.

As an emerging area within PLM, digital manufacturing supports the collaboration of several phases of the product lifecycle which are evolved from manufacturing initiatives such as design for manufacturability, computer integrated manufacturing, lean manufacturing, flexible manufacturing systems, etc. [2]. Digitization is leading the manufacturing into a new path due to advancements in technologies like robotics, 3D printing, human-machine interaction, automation and artificial intelligence.

This article presents the driving forces for transformation to digital and the advancement of traditional manufacturing to digital manufacturing. Simulation-based technologies like 3D Layout validation, Process and Plant simulation, Human ergonomics and Advanced Process Planning techniques as shown in Fig. 2 which allow for the experimentation and validation of various products, processes and production systems configurations for meeting the current requirements of manufacturing industry are explained.

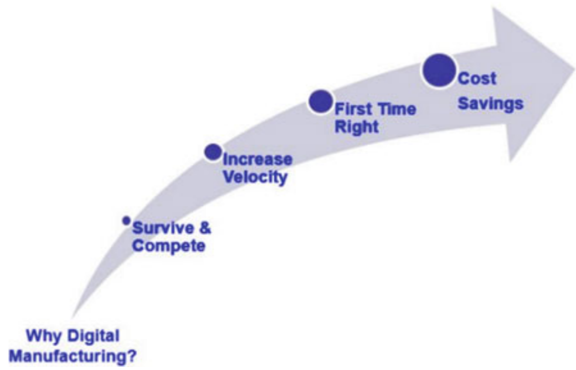


Fig. 1 Impact of digital manufacturing

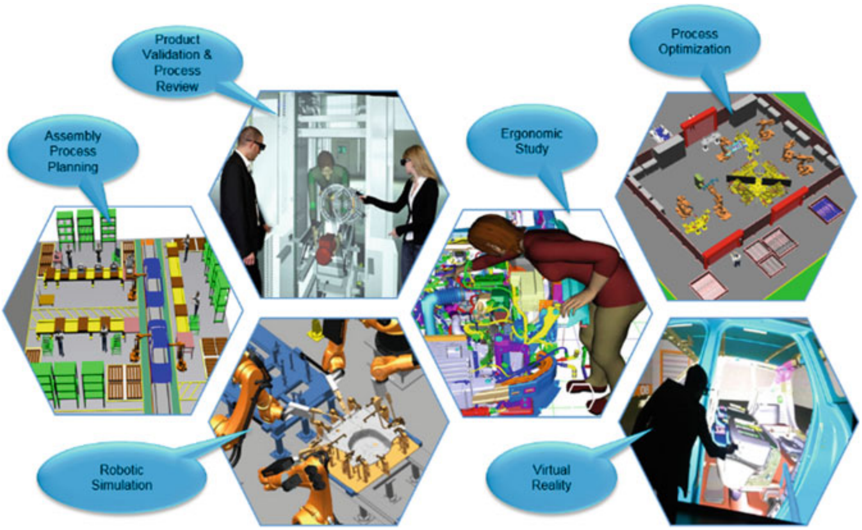


Fig. 2 Footprint of digital manufacturing

2 Traditional and Digital Manufacturing

The traditional manufacturing is a step by step process where the product is designed and drawings are sent to the shop floor for manufacturing the prototype and then the tool design and tryouts are carried out which is a tiresome process. Whereas, digital manufacturing is an approach in which the different stages run simultaneously, rather than consecutively as shown in Fig. 3. Concurrent engineering contributes to a reduction in product development time and time to market, leading to improved

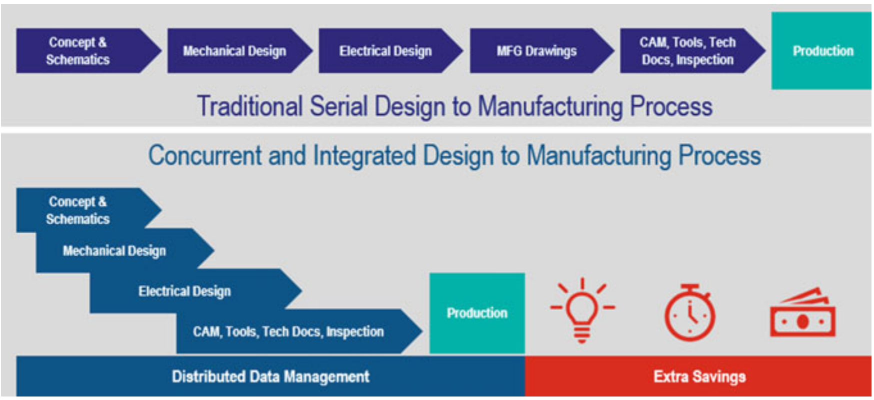


Fig. 3 Concurrent and integrated design to manufacturing process

productivity, throughput and reduced costs (i.e. resulting in both top and bottom-line improvement opportunities).

For checking the feasibility of manufacturing the product, designs and the processes are simulated virtually using digital manufacturing tools. Every phase of the production process is digitized from the design until the product is dispatched, including the supply chain management for efficient inventory control.

3 Driving Forces

The manufacturers are equipped with outmoded production facilities which reduce the adaptability to meet the current market demands. In this dynamic economy, industries are getting benefited by adapting new technologies to overcome these barriers. The driving forces for adapting digitization are as follows:

- Speed,
- Cost,
- Quality and
- Custom requirements.

In the past few years, the digitization tools such as virtualization, simulation, rapid manufacturing, cloud computing, data analytics, knowledge library and social networks are widely adopted by the industries for each phase of the product life cycle.

4 Digital Manufacturing Approach for Industrial Transformation

The methods and models of the Digital Factory will bring out a significant reduction in planning errors, planning time and change costs, thereby increasing the planning maturity to a great extent.

Tecnomatix Process Simulate has become one of the most widely used applications in manufacturing process design, enabling designers and stakeholders to identify the critical areas of their process and analyze the alternative solutions to enhance the performance of the manufacturing system.

The methodology for the application of these tools is as shown in Fig. 4.

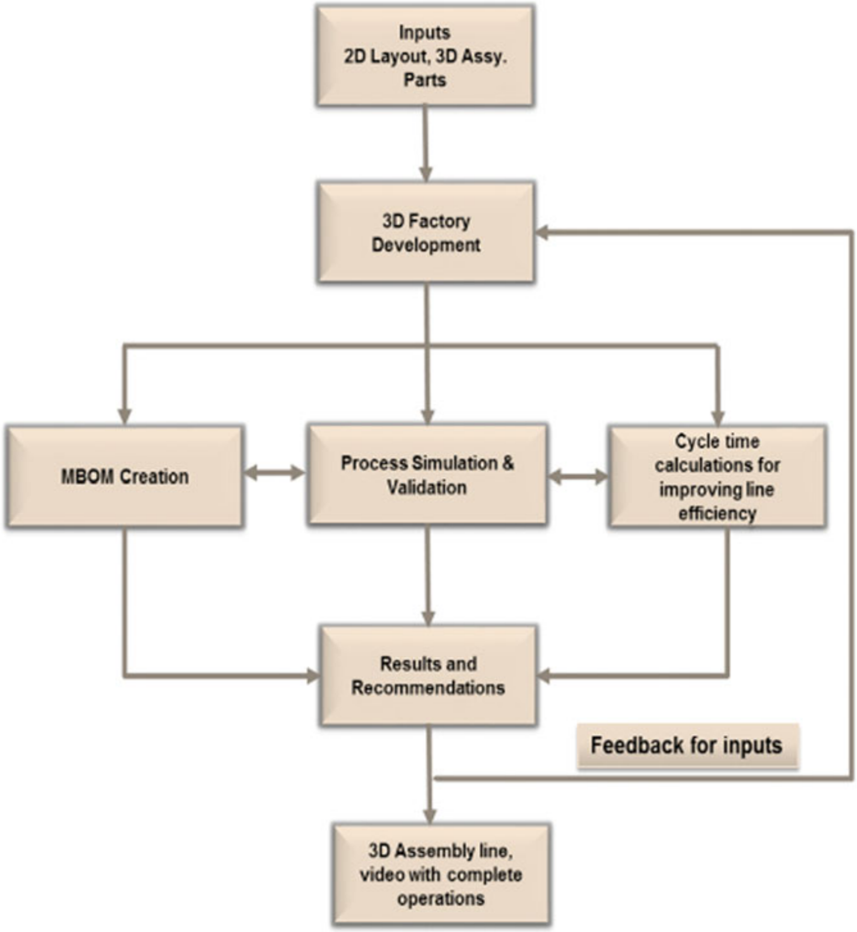


Fig. 4 Methodology of digital manufacturing

4.1 Digital Factory Planning

Factory layout planning plays a crucial role in the manufacturing sector while designing or redesigning production systems. Layout planning usually involves 2D CAD applications. Difficulties in communicating and discussing layout alternatives using such applications can lead to critical errors, yielding inaccurate process simulation models thereby producing inefficient results.

Whereas 3D layout creation will make modification and visualization easier and faster than the 2D Layout. Design flaws and issues can be identified and eliminated during the design phase, prior to physically building or modifying the factory.

Layout planning can be done considering the parameters related to machines, architectural data, workspace requirements and inventory management so that required storage space and the required number of carts/containers can be maintained for the production activities to happen without any interruption using different strategies like LIFO/FIFO for storing and removing of materials which in turn helps the plant team to plan right from the raw material stage till the dispatch of the finished goods to the customer.

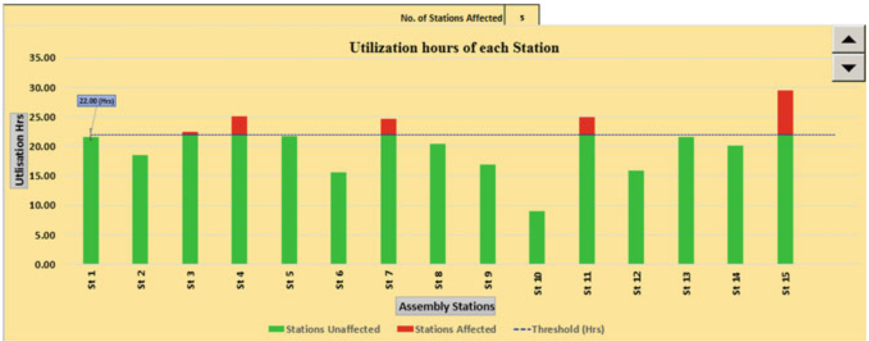
Re-using this 3D layout for simulation applications can save time by allowing us to assess more design configurations, and making the layout information efficient and valuable. In a nutshell, this will bring factories into production sooner with minimum modifications providing remarkable benefits in time, cost, human, machine and inventory management.

4.2 Time Study and Line Balancing

Manufacturing Process Planner tools provide a variety of time management solutions which help plant engineers clearly visualize value-added (VA) and non-value-added (NVA) activities. Process planners can analyze and validate activity time at various levels of the process structure using charts and reports and roll-up time estimates of different levels of process hierarchy [3]. Analysis of VA and NVA helps in balancing of multiple assembly lines with each other by reducing idle time of operator and machine by eliminating the non-value-added activities in the process and improving the cycle time for obtaining better JPH (Jobs per Hour).

4.3 Capacity Calculations

Capacity planning is the process of determining the production capacity needed by an organization to meet changing demands for its products. Capacity calculations are carried out to analyze the line imbalance and bottlenecks in the process at each station and address them well in advance to ensure the smooth flow and thereby increasing the utilization of the resources to the maximum to achieve targets and meet the customer demands on time. Various factors such as scrap rates, rejection rates, cycle time, line stoppages, machine breakdowns, Jobs per hour (JPH), inventory management, etc. of the plant, which plays a vital role in meeting the production volumes are deeply analyzed to eliminate the bottlenecks thereby increasing the assembly line efficiency and OEE so that it will pay the way for achieving the required production volumes. Graph 1 which is generated from the mathematical simulation shows the utilization hours of machines at each stage in the assembly. It gives a clear picture of stations that are under and over-utilized for the current required volume and helps the program team to identify and balance the assembly line by keeping all the stations equally efficient whenever there is a change in the required volumes.



Graph 1 Utilization hours of each station

A study was conducted on *Seat Assembly Line* using digital manufacturing tools with an objective of accommodating the passenger car seat sub-assembly next to the vehicle mainline. The challenge was to come up with the 3D layout concepts considering vehicle variants and volumes with line balance between seat sub-assembly zone and vehicle mainline.

We came up with multiple concepts of 3D factory layout taking into consideration the future plan for the manufacturing plant. With virtual validation of each of the concepts, an optimized 3D factory layout was finalized for sub-assembly and mainline as shown in Fig. 5, with optimum number of stations, operators and robots for seat sub-assembly to vehicle mainline assembly.

The optimized layout had a cycle time well within the mainline cycle time. With the newly added sub-assembly zone that is next to the mainline, time and

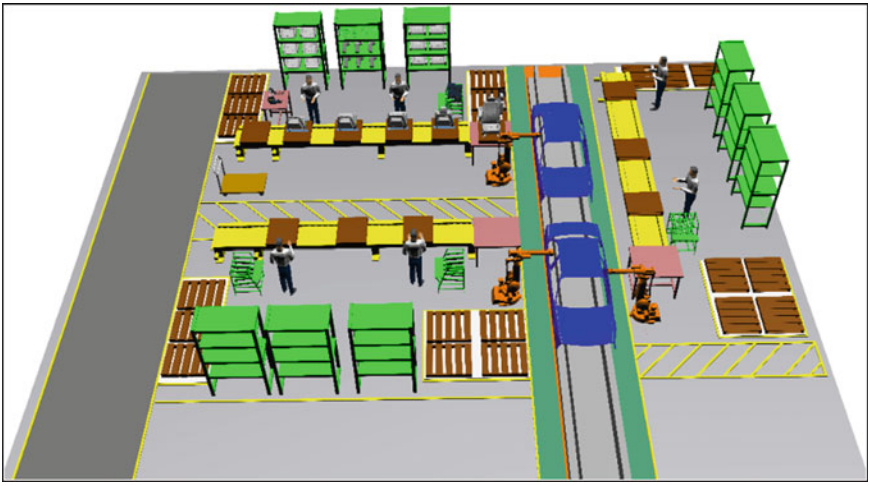


Fig. 5 3D layout of seat assembly line

cost involved in SCM were highly reduced. Virtual validation included simulation of robotic assembly, collision tests, reachability/accessibility, ergonomic study and cycle time with line balancing. Digital manufacturing not only saved the costs and process cycle time but also shortened the programme launch eliminating the number of iterations. Below picture shows the finalized layout for the seat assembly line.

4.4 Manufacturing Process Planning, Simulation and Validation

Process planning which is a preparatory step before manufacturing, for determining the sequence of operations or processes needed to produce a part or an assembly when done in a conventional way is unable to predict or capture the issue that will be faced after the implementation of the plan.

The feasibility of an assembly process can be verified using 3D Process Simulation tools which allow production engineers to determine the most efficient assembly sequence, catering for collision clearance between tools and the factory environment and identifying the shortest cycle time.

Manufacturing process verification in a 3D environment enables speed-to-market by allowing manufacturing organizations to virtually validate manufacturing concepts upfront—throughout the lifecycle of new product introductions. The ability to leverage 3D data of products and resources facilitates virtual validation, optimization and commissioning of complex manufacturing processes, resulting in the faster launch and higher production quality thereby well ahead of competitors.

A study on weld cell layout design for *body-in-white (BIW) weld process* is carried out for reducing the process cycle time with the help of digital manufacturing process. Initial process planning for BIW panel welding and concept design for welding fixtures was developed based on the number of panels and stages. Weld cell design and modelling were developed as shown in Fig. 6 by introducing the concept design of fixtures, robots, other resources and a virtual simulation was carried out to identify issues related to robot reachability and collision with its coordination tools and factory assets. Based on the study, necessary changes were incorporated in design or process flow. We have modified tools such as geo-stations, re-spot stations, load tables, grippers and gripper stands based on the multiple iterations performed virtually for process optimization. Virtual validation of weld cell layout has significantly reduced the time for proving the design. Therefore, robotic offline programming can be used in the real-time shop floor environment directly.

Fig. 6 3D layout of weld cell

4.5 Ergonomic Analysis and Simulation

Ergonomic study of the operator's activity for each and every stage is to be carried out by considering all the aspects related to human fatigue, operator's movement, repetitive tasks, material movements and many more. Issues related to operator fatigue causing Musculoskeletal Disorders (MSD) which impacts the production are identified and necessary changes in the process are implemented like using conveyors, material handling equipment, etc. to make the work easy for the operators. Ergonomics analysis is done to study the reachability, accessibility and visibility of the operator to perform a task with ease. Safety issues are also taken into consideration while performing the ergonomics study which helps in creating a comfortable and safe environment for the operator to work.

Prior to the execution of job, ergonomic conditions can be improved using human modelling in a virtual environment. Human-centred designs and operations can be analyzed with realistic models that can be scaled to match different region wise characteristics. We can test operational aspects of a wide variety of human factors, including operator safety (injury risk), operator comfort and fatigue limits, ensuring compliance with ergonomic standards during design and planning stage thereby avoiding the issues related to human performance and feasibility during the production stage.

By doing this study an easy and optimum way of performing the activities is finalized which helps in eliminating risks and decreases the time taken to complete the task. Feedback from the ergonomics study is considered during the development of 3D Layout and manufacturing process study to ensure that the operator doesn't face issues in reachability and accessibility in the manufacturing line. Figure 7 depicts

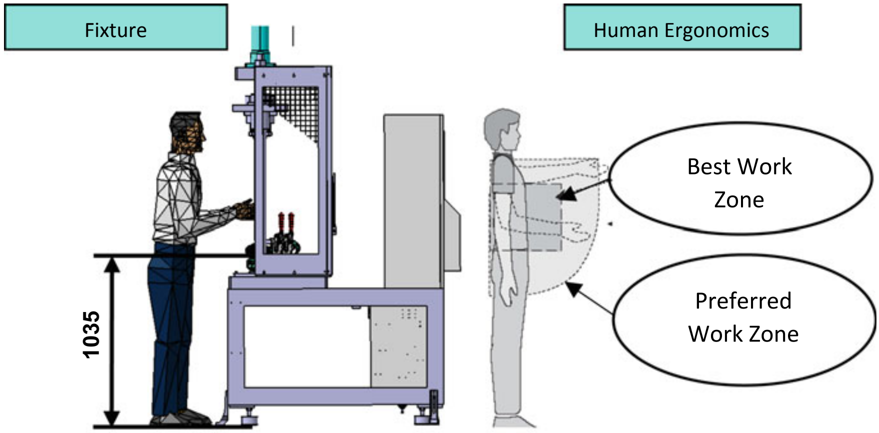


Fig. 7 Operator work envelope analysis

the best work zone for the operator which is considered for the fixture and assembly line development.

4.6 Offline Programming (OLP)

Offline Programming allows programming of the robots outside the manufacturing environment and avoids the production downtime caused by shop floor programming. Simulation allows studying multiple scenarios of a work cell before setting up the production work cell and the optimum solution can be taken as offline program. Common Mistakes made in designing a work cell can be virtually visualized and eliminated before manufacturing of the work cell.

Offline Programming is the unsurpassed way to maximize return on investment for robot systems. So that new programs can be easily adopted and the set up time can cut short from weeks to a single day, enabling the automation of short-run production.

5 Case Study on BIW Welding Process

A case study on BIW Welding Process for which digital concepts are applied to enhance the process in the existing line is presented to get an understanding of the application of the mentioned digital manufacturing processes.

The case study consists of an automated weld cell consisting of four robots which perform spot-welding for rear floor of Vehicle Underbody at two stations viz. one geo-stations and one re-spot station as shown in Fig. 8. Human intervention in this

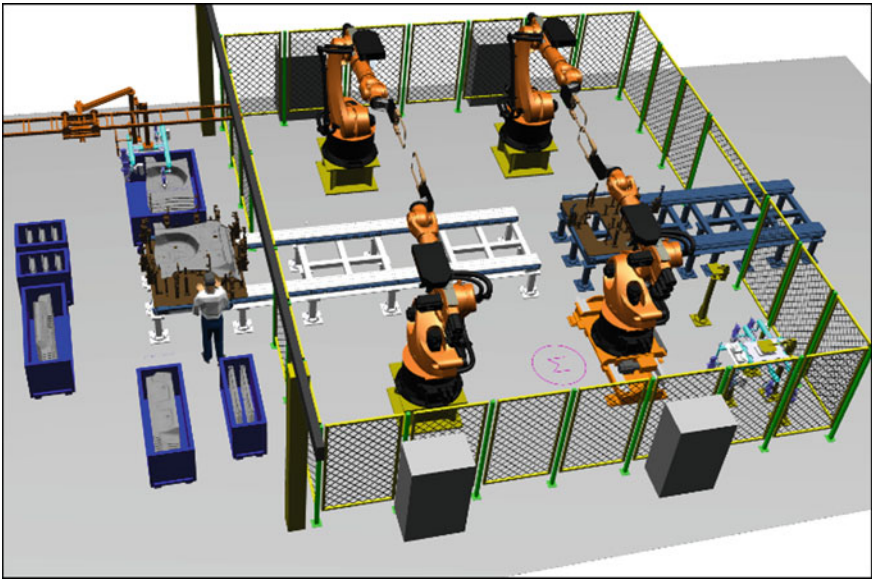


Fig. 8 3D layout of underbody rear floor spot weld process

process is for the initial loading of parts, while all the other activities in the process are automated thus improving the weld quality and achieving high JPH (Jobs per Hour). Automation of process helped in achieving higher dimensional accuracy, weld quality, low operational costs and less break-down time.

5.1 Development of 3D Layout

Development of 3D layout as shown in Fig. 8 had helped in visualizing the plant in a better way and assisted in process simulation. This also helped us to virtually check for space utilization, layout planning and also for checking if there is any interference with the surroundings. 3D layout consists of collaborative robots, welding fixtures and grippers which are taken further for virtual manufacturing.

5.2 Process Simulation

Virtual spot-welding environment is created for a complete weld line with robots, spot-welding guns and validated for the real-time issues as shown in Fig. 9. These issues are addressed prior to the implementation phase thereby reducing the shop floor

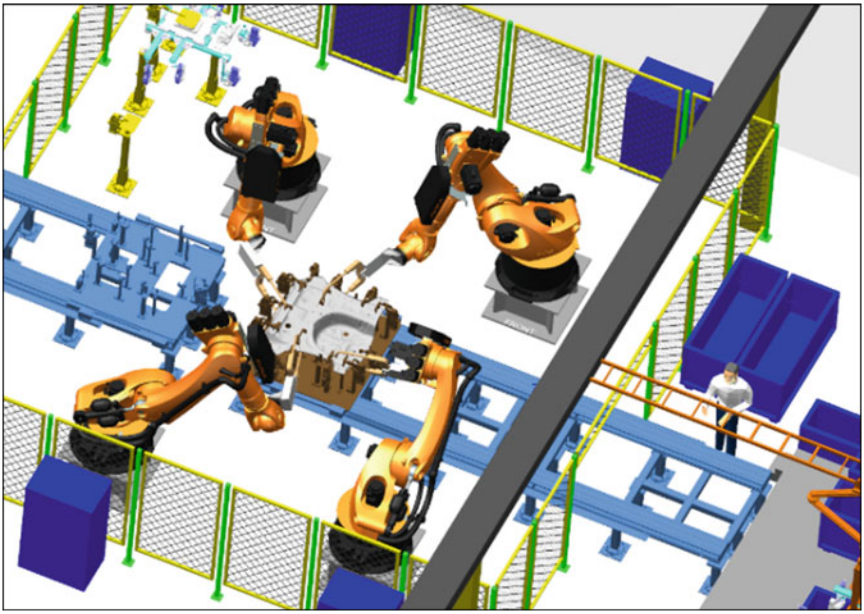


Fig. 9 Simulation process

development activities and shortening the launch phase depending on the complexity of the process.

Cycle time is calculated by creating the sequence of operations for adding the processes in order. Realistic robot simulation (RRS) and RCS (Robot Controller Software) assists in carrying out simulations of robot motion sequences accurately and robotic programs are delivered to the shop floor. Calibration functionalities enable us to precisely align the models of digital cells with actual layouts. After configuring and simulating operations can be downloaded as a program using OLP (Offline Programing) tools which can be directly fed to the robot on the shop floor.

5.3 MODAPTS and Ergonomics

MODAPTS (Modular Arrangements of Predetermined Time Standards) system is an instrument to improve ergonomics in the workplace. By using this system, activities are analyzed by considering operators performance and enable us to identify ways to make work easier through improved work and workplace design. Through MODAPTS, cycle time required to perform the activities is estimated by analyzing the various body movements utilized and the degree of movement needed.

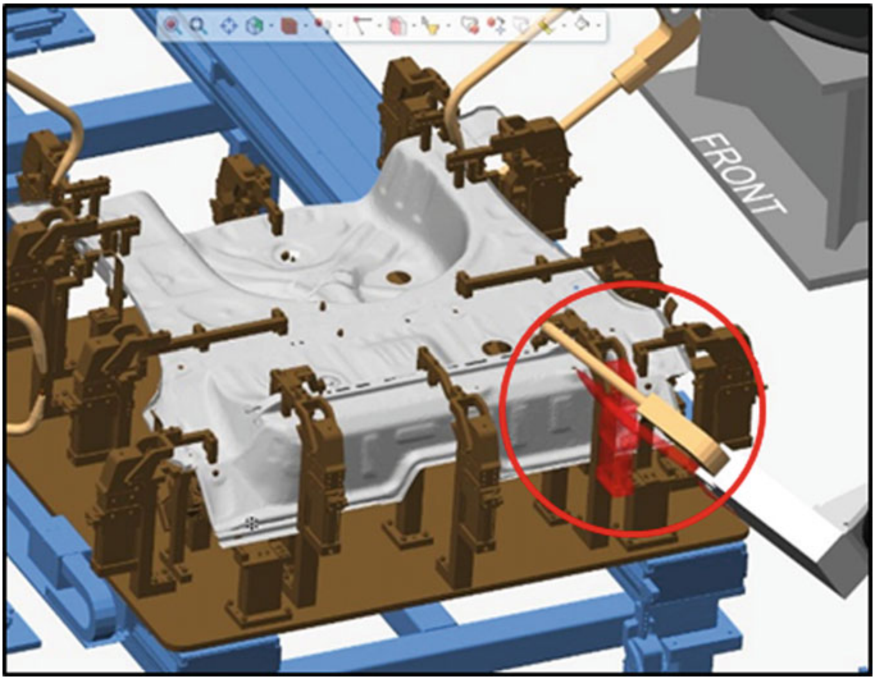


Fig. 10 Collision of weld gun with fixture

Human movements are studied in detail in the work environment to analyze the various ergonomic factors which lead to Musculoskeletal Disorders (MSD) and eliminate them to establish a safe environment for the operator.

5.4 Issues Identified

- Robot reachability and accessibility issues.
- Collision and near-miss with the car-part and fixtures (Figs. 10 and 11).
- Issues related to parts orientation and placement.

5.5 Results

- Cycle time arrived from the simulation was close to the estimation which is done based on the number of spots, sequence of operations and the robot movements, however, multiple iterations were carried for optimizing robotic trajectory, which has reduced the cycle time.

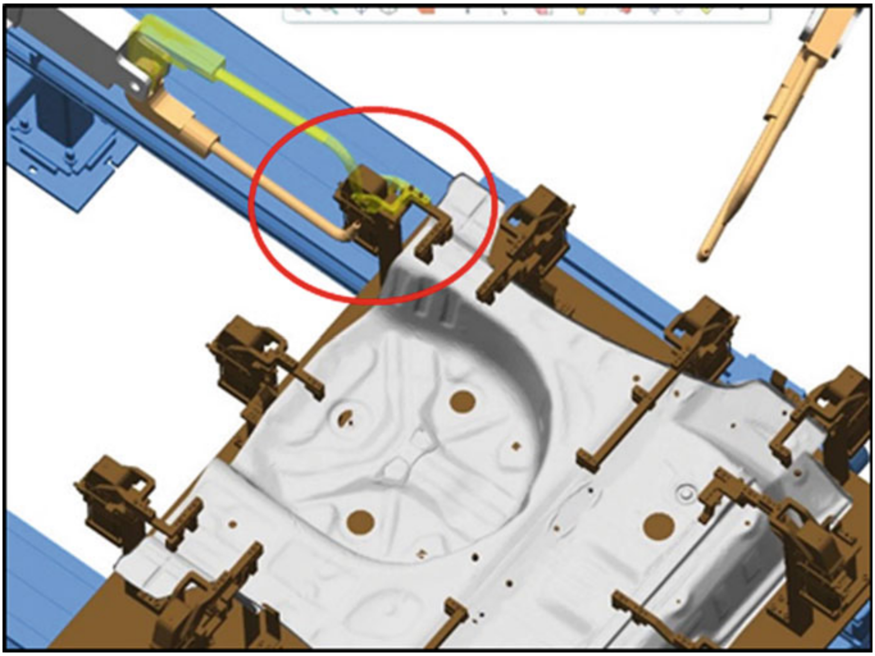


Fig. 11 Near miss of weld gun with fixture

- Optimum Layout and Robotic trajectory are defined.
- Cycle time is optimized by 25%.
- Co-ordinates of robotic simulations are off-loaded to robot as the robotic program.
- Time for Proving and tryouts is reduced.
- Time and cost of development are reduced.

6 Conclusion

Digital manufacturing not only assists in representing the factories, architecture, resources, machine systems equipment and human in virtual environment but also aids in analyzing the manufacturing as well as human activities using simulation-based technologies.

Thus, digital manufacturing is bridging the gap between the activities of product lifecycle by creating a product as well as process models simultaneously/concurrently so that the industry can operate under optimal layout, material flow and throughput. Also commissioning time and costs can be cut short by simulating the robotic and human activities in virtual environment before the production ramp-up.

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Implementation of Quality Information Framework (QIF): Towards Automatic Generation of Inspection Plan from Model-Based Definition (MBD) of Parts

Peethani Sai Ram and K. Deepak Lawrence

Abstract Smart manufacturing relay on digitalization that provides a seamless flow of information between various stages of design, manufacturing, and quality control of products. Digital manufacturing-based industrial environment requires the manufacturing systems to be integrated, flexible, adaptable, and automated. Present computer-aided systems fall short of interoperable integration among machines and systems. This paper covers interoperability and automation of Computer-Aided Inspection (CAI) systems by means of QIF standard as a major tool. This paper discusses the QIF standard, its structure, and the implementation methods of QIF. It describes the development of software tools using Python language for the generation of QIF files from MBD (STEP AP 242) and also the automatic generation of DMIS inspection plan from QIF file.

Keywords Automated inspection plan · Interoperability · STEP AP 242 · NIST STEP analyzer · Quality information framework (QIF) · DMIS

1 Introduction

There is an ever-increasing requirement for reducing the lead time of product realization with better quality attributes. The improvement in Internet-based information technology and communication helped worldwide distributed organizations to deploy a complex cluster of various software and hardware for the quick product realization and product life cycle management. Thus, the present-day complex digital enterprises demand to manufacture to be integrated, automated, and smart. This drives the manufacturing to move forward from traditional ways of doing the production to the digital way of manufacturing. This is the base for a new era of the industrial revolution, also called industry 4.0, which provides a smooth flow of information between various hardware's and software's using digital systems.

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A. Chakrabarti and M. Arora (eds.), *Industry 4.0 and Advanced Manufacturing*, Lecture Notes in Mechanical Engineering,
https://doi.org/10.1007/978-981-15-5689-0_12

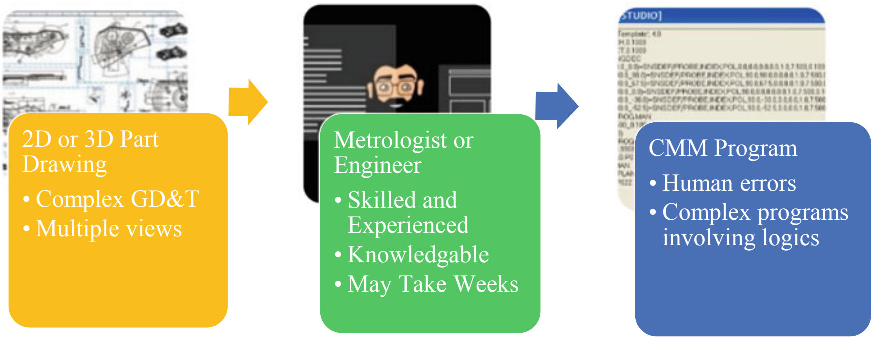

Fig. 1 Present computer-aided inspection

This smooth, seamless flow of information between different software systems mandates interoperability. Lack of this interoperability is lowering the industry competitiveness and hampering them; for instance, translators are used to translating data from one CAD to another CAD system, which incurs confusion and data loss. If there are n different software's in a company; it requires $(n - 1)$ translators. This creates a hunger for interoperability in digital systems. Interoperability can be achieved using open standards and neutral formats in which the loss of the data can be minimized and enormous time can be conserved. However, present computer-aided inspection systems fall short of this interoperability, and still, it takes a tedious time for inspection planning and measurements. The main reason for neglecting the measurement from the last few decades is due to the contested belief that it is not a value-added process and hence considered as one of the processes to be eliminated [1]. For instance, as shown in Fig. 1, take the case of an engineer who needs to do CMM programming from a drawing. It can take weeks to program a single part; it requires skilled CMM technician with knowledge of GD&T, CAD, and measurement. There can be a high risk of transcription and interpretation errors while developing CMM programs. Due to this, design engineers started considerable minimization of the use of GD&T in designs despite the functional demand. These issues could be avoided by the complete automation of the inspection plan generation from CAD models. Quality Information Framework proposed by Digital Metrology Standards Consortium (DMSC) is a step towards achieving automation of quality-related manufacturing functions in an organization. An overview of the QIF standard is presented in Sects. 1.1 and 1.2 consist of an introduction to DMIS standard.

1.1 Quality Information Framework (QIF) and Its Structure

The QIF standard defines an integrated set of information models that enable the effective exchange of metrology data throughout the entire manufacturing quality measurement process—from product design to inspection plan to execution to analysis and reporting [2]. It helps to enable the capture, use and reuse of metrology-related information throughout the Product Lifecycle Management (PLM). DMSC is responsible for the maintenance, development, and support of the QIF standard. The QIF information models are provided as files that are written and structured in XML Schema Definition Language (XSDL). The models in Version 2.1 consist of six application model schema files plus a library of schema files (see Table 1) as shown in Fig. 2.

QIF library	It consists of information items used by all applications.
QIF M.B.D	It deals with CAD data plus product manufacturing information (PMI).
QIF Plans	It deals with plans for quality measurement.
QIF Resources	It describes hardware and software resources used for inspection.
QIF Rules	It describes practices to be used in an inspection.
QIF Results	It deals with the results of measured parts.
QIF Statistics	It conveys analysis of multiple part inspections.

Every application model exports file with the same extension (.QIF) but add data to its defined variables and attributes in the QIF file. The contents of the schema are followed according to ASME Y14.5-2009 and DMIS 5.2. The flow of QIF file starts with the generation of CAD & PMI data and is exported as QIF MBD format which is, in fact, an XML file but with W3C defined QIF XML schema. Quality planning systems import this MBD and generate plans (what's), then import Resources and Rules information and pass on plans (what's and how's) QIF workflow is shown in Fig. 3.

Table 1 QIF library directory

QIFLibrary (directory)
Auxiliary.xsd
Characteristics.xsd
Expressions.xsd
Features.xsd
GenericExpressions.xsd
Geometry.xsd
IntermediatesPMI.xsd
Primitives.xsd
PrimitivesPD.xsd
PrimitivesPMI.xsd
Statistics.xsd
Topology.xsd
Traceability.xsd
Units.xsd
Visualization.xsd

Fig. 2 QIF application models and library (*Source* ANSI/QIF Part 1–2014, p. 2)

Fig. 3 QIF Workflow

Users of this QIF information model need not implement the entire model, any of the provided six application models can be used single-handedly for exchange of product quality data between the various software systems, as stated earlier only concerned data is added to its allocated variables. QIF library schemas are used by application model schemas by reference using the XML schema's "include" statement. QIF also consists of feature LOng Term Archiving and Retrieval (LOTAR) of product and technical data: it is a standard that describes the product life cycle management mainly used in military and aerospace applications [2]. In QIF, if the complete model is built using XSD files, then it is called a schema. A sample XSD schema file is shown in Fig. 4. However, the complete model may consist of several different schema files of information items. The actual model consists of a main root schema file and then its subordinate schema files, which are referenced in root schema by using 'include' directive. For example, QIF Document is the complete application schema that will have a top-level schema file named QIFDocument.xsd, which consists of other subordinate application model schemas included like QIF Rules, QIF Plans, etc. As subordinate schemas could refer to library schemas, and thus QIFDocument schema consists of all QIF schema files. An XML file conforming to the schema is called as an instance file and will have QIFDocument as the root. Figure 5 shows a sample XML file that conforms to the XSD schema of Fig. 4.

```
<xs: element name="Family">
  <xs: ComplexType>
    <xs: sequence>
      <xs: element name="Husband_Name" type="xs:string"/>
      <xs: element name="Wife_Name" type="xs:string"/>
      <xs: element name="Child_Name" type="xs:string"/>
    </xs: sequence>
  </xs: ComplexType>
</xs: element>
```

Fig. 4 Sample XSD schema

```
< Family >
  < Husband_Name >Eddy</ Husband_Name >
  < Wife_Name >Mary</ Wife_Name
  < Child_Name >Charles</ Child_Name >
</ Family >
```

Fig. 5 Sample XML file conforming to Fig. 4 schema

1.2 Dimensional Measuring Interface Standard (DMIS)

DMIS is one of the most used and recognized standards in dimensional metrology internationally. This standard helped significantly in the improvement of interoperability between CMMs and traceability of measurement processes. The maintenance, development, and support of this DMIS are also taken care of by the DMSC only. DMIS can be defined as a programming language that is in ASCII format. It allows the execution of inspection programs between different measuring devices such as CMM, optical, laser, and video-based measurement systems [3]. It provides communication between the CAD/CAM systems and metrological devices bi-directionally. These DMIS files must be post-processed (or translated, tailored to relevant measuring software) so that they can be used by measuring machines.

2 Literature Review

Zhao et al. [4] suggested the need for the development of open-source QIF library for the widespread application of QIF standards in the industry. Michaloski et al. [5] indicated that the QIF library and QIF applications provide generic templates for the user to instantiate for their own implementations, thus enhancing the code reuse and consistency for the implementations. Sathi and Rao's [6] presented work about the automated generation of inspection planning by taking STEP file as input and tested the results using CMM. Lipman et al. [7] developed software tools for the extraction of PMI from STEP files. Emmer et al. [8] suggested neutral files like I++DMS and I++DME, QIF for measurement integration. The literature reported regarding the implementation of QIF standard is limited. This work reports the preliminary attempts for the implementation of QIF using source code binders.

3 QIF Software Developments and XML Implementation

Implementation of QIF standard in XSD schema allows automatic syntax and consistency checking of the standard itself. Software implementation of this standard can take advantage of free or low-cost source code generation tools that automatically consume and produces QIF Document instance files in XML format [2]. At the National Institute of Standards and Technology (NIST), QIF has been applied to many different types of applications. For instance, CodeSynthesis and Xerces XML/XSD parser is used to produce various QIF programs useful in the end-to-end quality management, as shown in Fig. 6.

These include parsing the QIF XML into C++ format, serializing the native C++ format to QIF XML, generation of Structured Query Language (SQL) data tables from the QIF XSD, etc. DMSC maintains a QIF community hub in GitHub which helps and provides free tools suggesting the implementation of the QIF using source code generators. There are many other source code generators available that do the same purpose, such as CodeSynthesis provides in C++, JAXB for Java, etc.

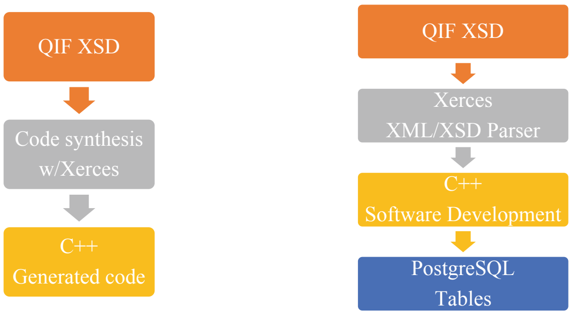

Fig. 6 QIF XML solution space

3.1 Source Code Binders

In general, a code that is human readable, structured, and programmed is called a source code (c++, python, C#, etc.). When this source code is provided to the corresponding language compiler, it produces another code called as object code. Object code is a non-human readable and a machine-readable code which is an executable file that can be executed to perform the required function. Binder is a software mechanism that performs binding and conversion to a required programming language. For example, a binder combines numerous files into a single executable file in a required programming language by creating classes corresponding data structures from parent files.

In this work, PyXB (pixbee) Source code Binder is used for binding XSD schema files. PyXB is a pure PYTHON package that generates PYTHON source code for classes that correspond to the data structures defined by the XML schema. Such generated classes provide a bi-directional conversion between XML documents and PYTHON objects. In present work, all QIF XSD files are combined into a single schema file, namely QIF Document. All the data structures in the QIF XSD files namely type definitions are converted to classes in PYTHON language, for instance, QPId XSD type as shown in Fig. 7 is converted to QPId class as shown in Fig. 8. Hence, for each type of definition in QIF XSD, there will be a class defined in the source code binder generated PYTHON file. These classes are those which can be taken as input or imported in other source code programs and software can be developed according to our requirement and function. In this way, XSD schema provided can be combined and made useful for implementation.

```
<xs:element name="QPId"
    type="QPIdType">
    <xs:annotation>
      <xs:documentation>
        The required QPId element is the UUID for this document
        identifying it uniquely and allowing it and its elements to be
        referenced from other QIF documents.
      </xs:documentation>
    </xs:annotation>
</xs:element>
```

Fig. 7 QPId type in QIF schema

```
class QPIdType (pyxb.binding.datatypes.token):
    _ExpandedName = pyxb.namespace.ExpandedName(Namespace, 'QPIdType')
    _XSDLocation = pyxb.utils.utility.Location('C:\\Users\\om\\Desktop\\sample\\qif-
community-master\\_legacy\\qif-2.1\\bindings\\python\\QIFLibrary\\Primitives.xsd',
1222, 2)
    _Documentation = '\n        The QPIdType (QIF Persistent Identifier Type) is the
text\n        representation of the universally unique identifier described in\n
the standard ISO/IEC 9834-8. As a number, it has 128 bits. As a\n        text string
it is represented by 32 hexadecimal digits displayed in\n        five groups separated
by hyphens in the form 8-4-4-4-12, for a\n        total of 36 characters. example:\n
fd43400a-29bf-4ec6-b96c-e2f846eb6ff6\n      '
QPIdType._CF_pattern = pyxb.binding.facets.CF_pattern()
QPIdType._CF_pattern.addPattern(pattern='[A-Fa-f0-9]{8}-[A-Fa-f0-9]{4}-[A-Fa-f0-9]{4}-
[A-Fa-f0-9]{4}-[A-Fa-f0-9]{12}')
QPIdType._InitializeFacetMap(QPIdType._CF_pattern)
Namespace.addCategoryObject('typeBinding', 'QPIdType', QPIdType)
 module typeBindings.QPIdType = QPIdType
```

Fig. 8 PyXB generated python class for QPId type in QIF schema

3.2 A Framework for QIF to DMIS

As explained earlier using PyXB source code binder XML XSD schema files are combined, and corresponding classes are created in a single file, named as QIF Document. Hence, the program has to be developed to import those classes required for the generation of DMIS code. Pycharm PYTHON Integrated Development Environment (IDE) has been used for this development of the program. IDE assists while programming showing errors and it has inbuilt and installed modules of PYTHON which can be imported directly, it will have a self-compiler by which one can run the programs in it.

Steps involved in the development of the program are as follows:

- Importing of modules and classes required for various functions in the program.
- Importing the QIF file.
- Parsing the QIF file using Document Object Model (DOM) into a variable.
- Importing of required type definition classes from QIF Document.
- Comparison of defined convections and names between QIF Document and parsed QIF file.
- Extracting data from parsed QIF file, using it to write DMIS program and export DMIS file.

Document Object Model (DOM) is an Application Programming Interface (API) that can be imported into PYTHON program; it is used to parse the document in objects maintaining the relationship between the objects. Simply DOM parses the document into tree structure which will have child and grandchild elements.

DMIS is a feature eccentric and requires points, dimensions on the features to measure and compare. Hence, before explaining the structure in program, convections and type definitions defined in QIF schema are to be explained. All feature related type definitions are written in FeatureTypes.xsd, which has to be imported from the library into the main root schema. This FeaturesTypes.xsd consists of 28 feature types defined in it. Features in QIF are defines using four aspects, namely: Definition, Nominal, Actual, and Item. In a QIF instance file, each feature data

```
<CylinderFeatureDefinition id="22">
  <Diameter>10</Diameter>
</CylinderFeatureDefinition>
```

Fig. 9 CylinderFeatureDefinitionType (*Source* ANSI/QIF Part 1–2014, p. 41)

```
<CylinderFeatureNominal id="23">
  <FeatureDefinitionId>22</FeatureDefinitionId>
  <Axis>
    <AxisPoint>40 40 0</AxisPoint >
    <Direction>0 0 1</Direction>
  </Axis>
</CylinderFeatureNominal>
```

Fig. 10 CylinderFeatureNominalType (*Source* ANSI/QIF Part 1–2014, p. 41)

object consists of a unique identifier, and the connections between these objects are communicated by references to the identifiers.

Feature Definition: This data object is intended to be reusable that is common to feature types, and it consists of information like the diameter of cylinder or circle, etc. as shown in Fig. 9. A single feature definition can be referenced by many feature nominal data objects.

Feature Nominal: This data object adds additional unique feature data to the feature definition defining a particular instance of a feature, as shown in Fig. 10. For example, this provides location and axis vector of a circle referencing diameter from **CircleFeatureDefinitionType**.

Feature Item: This data object characterizes an instance of a feature at any stage of the metrology process, for instance, before or after a feature has been measured as shown in Fig. 11. It consists of the name assigned to feature, a reference id to **FeatureNominalType,** and an optional reference to **FeatureDefinitionType**.
Feature Actual: This data object consists of measured information about the feature, for instance, about actual location and diameter of the feature defined as shown in Fig. 12. It will have a reference to the **FeatureItemType**.

From above, it is clear that the feature is defined with four aspects, and these will have data in QIF file. So this feature data has to be extracted from the QIF

```
<CylinderFeatureItem id="27">
  <FeatureNominalId>23</FeatureNominalId>
  <FeatureName>Hole_1</FeatureName>
  ...
</CylinderFeatureItem>
```

Fig. 11 CylinderFeatureItemType (*Source* ANSI/QIF Part 1–2014, p. 43)

```
<CylinderFeatureActual id="31">
  <FeatureItemId>27</FeatureItemId>
  <Axis>
    <AxisPoint>40.002 39.994 0</AxisPoint>
    <Direction>-0.001 0 1</Direction>
  </Axis>
  <Diameter>10.003</Diameter>
</CylinderFeatureActual>
```

Fig. 12 CylinderFeatureActualType (*Source* ANSI/QIF Part 1–2014, p. 44)

```
$$ Plane nominal DAT_A
F(DAT_A)=FEAT/PLANE,CART,1.0,4.0,6.0,0.0,0.0,1.0
MEAS/PLANE,DAT_A, 1
PTMEAS/CART, ,1.0,4.0,0.6,0.0,0.0,1.0
GOHOME
ENDMES
```

Fig. 13 DMIS result of above code

file, and corresponding DMIS feature measuring command has to be programmed. For instance, take DOM parsed QIF file is saved into qifdoc. After checking all FeatureTypes have data in it, and whether they are having the same valid referencing ids between them, the data is copied into local variables, namely featItem, featNom, and FeatDef, etc. By using if and for loops, walking through the n number of features defined they are converted to DMIS format. A sample of the program to measure plane feature with dimensions is represented in 3.2.1, and its result DMIS format is shown in Fig. 13. If any tolerance data or other characteristic data such as Datum Definitions are required to be included, then separate functions have to be created by importing corresponding type definitions from the QIF Document, and extracted data is represented in DMIS format. In a similar way, the program could be extended for other features to produce in DMIS format.

3.2.1 Sample QIF to DMIS Program Code for Plane Feature

```
for featItem in qifDoc.Features.FeatureItems.FeatureItem:
    # walk through the list of feature nominals...
    for featNom in
qifDoc.Features.FeatureNominals.FeatureNominal:
        # the item->nominal link is optional
        if featItem.FeatureNominalId is not None:
            # ...to find the associated feature nominal
            if featNom.id == featItem.FeatureNominalId.value():
                # walk through the list of feature
                definitions...
                for featDef in
qifDoc.Features.FeatureDefinitions.FeatureDefinition:
                    # ...to find the associated feature
                 definition
                    if featDef.id ==
featNom.FeatureDefinitionId.value():
                        # we have all aspects: item, nominal and
                 definition, make sure they're all the same type
                         if (type(featItem) is
                         QIFDocument.PlaneFeatureItemType) & \
                             type(featNom) is
                         QIFDocument.PlaneFeatureNominalType) &
                             type(featDef) is
                        QIFDocument.PlaneFeatureDefinitionType):
                                  # we have a matched set of
                                  plane aspects
                                  planNom = featNom
                                  # compose the feature nominal
                                  label
                                  flabel = "F(" +
                                  featItem.FeatureName + ")"
                                  # F(PLN1) for example
                                  #composing the nominal feature
                                  definition
                                   F(PLN1)=FEAT/PLANE...
                                  DMIS_OUTPUT = flabel +
                                  "=FEAT/PLANE"
                                  # cartesian
                                  DMIS_OUTPUT += ",CART"
                                  # nominal xyz location
                                  p += "," +
                         str(planNom.Location.value()[0]) + ","
                         + str(planNom.Location.value()[1]) +
                         "," + str(planNom.Location.value()[2])
                                  # ijk vector
                                  p += "," +
                         str(planNom.Normal.value()[0]) + ","
                 + str(planNom.Normal.value()[1]) + ","
                         +str(planNom.Normal.value()[2])

                                  DMIS_OUTPUT += P
                                  # measuring nominal xyz
                                  location
                                  DMIS_OUTPUT +="\nMEAS/PLANE,"+
                                  featItem.FeatureName + ", 1"#
                                  MEAS/PLANE...
                                  DMIS_OUTPUT +=
                                  "\nPTMEAS/CART,"
                                  # PTMEAS/CART...
                                  DMIS_OUTPUT += p
                                  DMIS_OUTPUT += "\nGOHOME
                                  nENDMES"
                         break# definition loop
            break# item loop
```

4 Conclusion

This paper addresses the integration of MBD based CAD and Inspection planning by using QIF 2.1, an ANSI standard. The successful implementation of DMSC's QIF is expected to provide a complete set of specifications required for seamless and effortless integration of manufacturing quality systems. This paper discussed the Python-based implementation of two application models of QIF, namely, Generation of QIF from MBD (STEP) and Inspection planning generating DMIS file, which is a neutral file format. There are also other application models of QIF standards such as QIF Plans, QIF Statistics that are required for the whole integration of QIF based automation. As QIF is provided free, it can be integrated and can take advantage of several programming languages for the development of various metrology hardware and applications. QIF is continuously being developed, and it is expected that it may include many other new integration solutions for the full automation of manufacturing quality systems.

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Building of a Cloud Factory—A Platform for Digital Manufacturing

Guruprasad Kuppu Rao, Jeet Palavwala, and Shubham Saxena

Abstract This paper presents a case study of building of a cloud factory, a name given to digital order processing. This is achieved with the help of a Web-based interface as front end to capture inputs. The inputs are processed by a set of back end programs. The output will be the price and can trigger order placement if confirmation is received. This is an automation of order processing and plays an important role in future smart manufacturing regime under Industry 4.0. It widens the reach to customers and helps deliver value. The proposed model has been tested successfully.

Keywords Industry 4.0 · Industrial Internet of things (IIoT) · Additive manufacturing · 3D printing · Sustainable development · Cloud computing · Digital order processing

1 Introduction

Since the dawn of civilization, humans have been developing new tools to cope and survive. We can see three distinct human abilities: empirical, cognitive and hand power. Through empirical inputs drawn from our senses, humans discovered tools such as wheels, fire and hand tools. What they lacked was power. Late eighteenth century heralded the birth of the first Industrial Revolution which gave us access to steam power. It opened up large-scale production. This led to mechanization and rapid transportation. Discovery of oil and electricity further improved power and its transformations. This gave us the industrialized world with assembly line which

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A. Chakrabarti and M. Arora (eds.), *Industry 4.0 and Advanced Manufacturing*, Lecture Notes in Mechanical Engineering,
https://doi.org/10.1007/978-981-15-5689-0_13

we can call as second Industrial Revolution. In the late nineteenth century, solid-state electronics opened up new opportunities in computation. Computation led to automation and information transmission. CNC, Internet and robots heralded the age of automated production. This many refer to as the third Industrial Revolution. Gordon Moore of Intel predicted an increase in miniaturization and computing power and the falling cost of computing. This prediction was not only proved to be on track, but it surpassed it. This parallelly helped in many areas of industry such as IT hardware, sensors, telecommunication and high-speed Internet. These have led to extreme optimization and ultra-computing leading us to artificial intelligence, autonomous robots and digital fabrication. This will lead to economic competitiveness [1]. This concept of an emerging new regime of extreme computing enabled production is called the fourth Industrial Revolution or Industry 4.0. This enables to deliver customized products [2] and solutions to customers directly. This production platform is also called as cyber-physical systems. This will trigger disruptive new business models [3] such as Amazon, Uber to make and deliver just one product custom made. Empirical needs are largely met by a set of sensors and power needs by robotics and CNC. What remains with humans is cognition and thinking. Even a large part of logical thinking can be done by machines powered by artificial intelligence (Fig. 1).

The first three Industrial Revolutions are capital intensive, delivered value through improved mass production. They however, fail to deliver value for small batch quantities with the same type of production infrastructure. This necessity led to a new invention called 3D printing or additive manufacturing. The way products are made got a new agile option. The new set of technologies called 3D printing has many early approaches such as photo sculpture was invented by Willeme in 1860 [4], Blanther who proposed layers to generate topography [5].

As per the ASTM standards, “additive manufacturing (AM)” can be classified as a “process of joining materials to make objects from 3D model data, usually layer upon layer”, [6]. They are a set of technologies popular as SLA, SLS, LOM, MJF, DMLS, SLM and more [7]. The technology which started as a rapid prototyping option in the 1980s has emerged as agile option: additive manufacturing (Fig. 2). The demand for

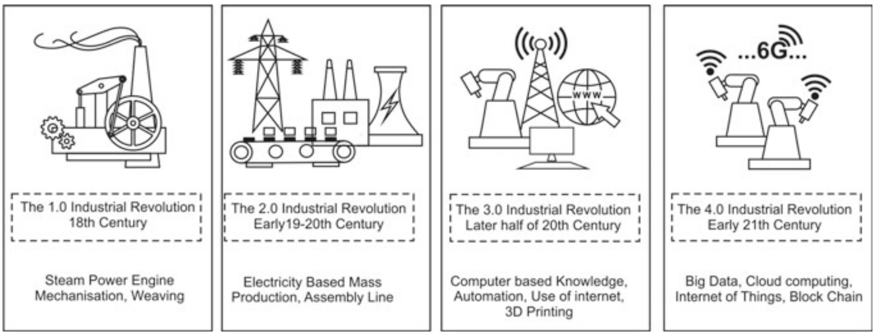

Fig. 1 Industrial Revolutions existing through ages

Fig. 2 Evolution from rapid to additive manufacturing technologies

customization has forced enterprises to look for these agile production technologies [8], and they need a customer touchpoint to gather requirements as well as payments. This calls for a sound IT infrastructure which is linked to the production system. This whole process needs a complex integrated structure [9]. German govt proposed cyber-physical production system in which manufacturing and logistics systems work in synchronization using globally available information and communications network [10].

2 Literature Review

The early concepts of Industry 4.0 were published by Kagermann in 2011 and were subsequently an Industry 4.0 manifesto published in 2013 by the German National Academy of Science and Engineering [11]. They called it as factories of the future [12]. In the USA, the concept is promoted by the Industrial Internet Consortium [13]. In the transformation of manufacturing processes into a fully digitized and intelligent one, AM service providers are offering the option to place orders online.

Examples for such commercial online portals are i.materialise, Shapeways and Sculpteo. To the best of our knowledge, an integrated assessment of potentials (and part screening) is so far not state of the art [14].

The production should be faster and cheaper with the use of additive manufacturing technologies like fused deposition method (FDM), selective laser melting (SLM), selective laser sintering (SLS) and multi jet fusion (MJF) [7]. As the needs of the customer are changing continuously, the challenge of increasing individualization of products and reducing time to market are faced by many companies. These challenges they encounter in particular with increasing digitization, IT penetration and networking of products, manufacturing resources and processes [8]. Decreasing product life cycles in combination with the growing demand for customized products asks for further transformation towards organization structures which lead to increased complexity [9]. Figure 3 shows the main components of Industry 4.0 and the place of AM.

In recent times, the first AM service providers offer the option to place orders online. Examples for such commercial online portals are i.materialise, Shapeways and Sculpteo. To the best of our knowledge, an integrated assessment of potentials (and part screening) is so far not state of the art [14].

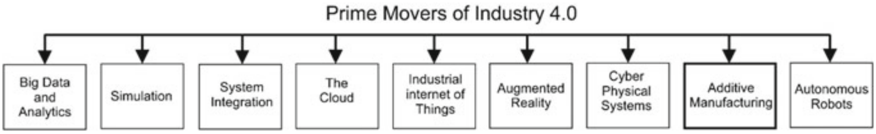

Fig. 3 Main prime movers of Industry 4.0

3 Functional Blocks of the System

The aim of the platform is an automation of the order processing for additively manufactured parts in a Web-based environment. On the one hand, the platform builds the communication interface between the customer and the manufacturing service provider. On the other hand, it supports the service provider in the processing of orders and inquiries. Important functional blocks of the automation system are shown in Fig. 4.

Each of these are explained briefly explained below:

- **Web Server with e-Commerce**: A Web server is a computer that is used to host an Internet Website. The term also refers to the program that runs on such a computer. Typical Web server programs are Microsoft IIS (Internet Information Services) and Apache. A Web authoring tool is used to create the front end of an e-commerce Website. They range from basic HTML text editors (like Notepad++) to more complex graphics authoring tools and content management system (CMS) with built-in frameworks and debugging tools.
- **Server-side 3D File Processing Software**: The 3D server, technically, performs three parallel processes that communicate by shared data repositories. The 3D request process manages requests for G-buffer cube maps sent by the clients. It can sort these requests according to their priority and dispatch these requests to

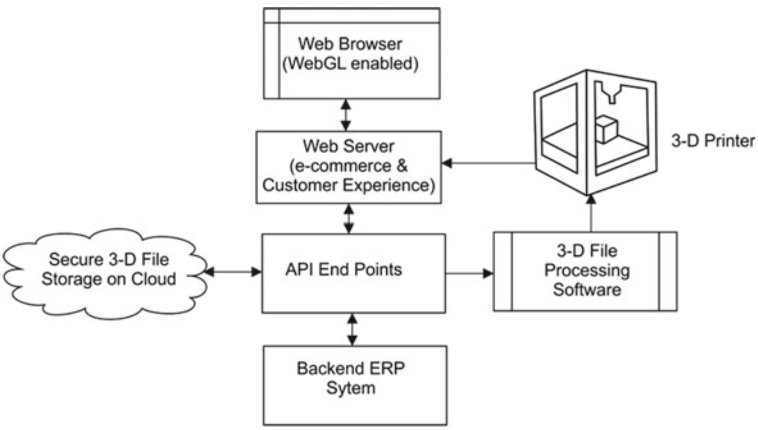

Fig. 4 Functional blocks of the cloud factory

available 3D rendering processes that are responsible for image synthesis and scene management. It accesses the 3D scene database, constructs and optimizes the corresponding scene graph and implements the core 3D rendering algorithms.
- **Client-side 3D Model Viewing and Shading**: The 3D client application provides a graphical user interface and is responsible for interactive display of and user interaction with the reconstructed 3D scene, including the request management. Therefore, G-buffer cube maps generated by the 3D server are transmitted to the client that manages these textures using a local cube map-cache. To render a reconstructed scene, the client builds a local scene graph that primarily consists of cube map geometry and textures.
- **Pricing Algorithms**: The costing of a component is based on certain analytical models (e.g. ABC cost model) which are derived specifically for 3D-printing. All of these models are based on certain assumptions and written in such a way so that they will result in accurate costing of the product. Nowadays, algorithms are getting improved day by day to compute the total cost associated with product development.
- **Cloud Data Storage**: Cloud storage is a cloud computing model that stores data on the Internet through a cloud computing provider who manages and operates data storage as a service. It is delivered on-demand with just-in-time capacity and costs and eliminates buying and managing your own data storage infrastructure. This gives you agility, global scale and durability, with "anytime, anywhere" data access.
- **API's**: An application program interface (API) is a code that allows two software programs to communicate with each other. APIs are made up of two related elements. The first is a specification that describes how information is exchanged between programs, done in the form of a request for processing and a return of the necessary data. The second is a software interface written to that specification and published in some way for use.
- **Backend ERP Systems**: Enterprise resource planning (ERP) software is usually referred to as back end management software, particularly when it is being distinguished from its counterpart customer relationship management (CRM). ERP software lets you manage every aspect of the business from one software system. By managing the finance, production, quality, logistics and HR in one package, it eliminates loss of information and data duplication which contributes to human errors and loss of profits slowing down production and delivery times.
- **Internet of Things (IoT)**: The Internet of things is the concept to connect objects between themselves to share data. The shared information can come from human behaviour or external factors. This is made possible by connecting our objects using electronic parts, sensors, software and the Internet or specific networks created for IoT. Thus, data can be exchanged between objects, without human action.

A typical example of IoT is a connected fridge, with captors that detect that you finished some of your basic aliments (eggs, milk, etc.) and automatically order them for you right away. This technology is used by a wide range of professional sectors, from consumer goods to defence. We are not using this right now but can be used to monitor machines and feed the data to cloud software.

The system shows a hierarchical nature to execute the task of order delivery.

The system typically has a front end and a back end. A Web login ensures authorized user access. Then, the system is ready to take inputs that trigger internal computations. At each stage, the system seeks approvals by the user. Control is a closed-loop and ensures final order punching and subsequent delivery. Architecture/anatomy of the system is kept in a way to offer flexibility and affordance to incorporate changes.

4 Testing of the Cloud Factory

A total of 30 dummy orders were punched of varying product type to test the ruggedness of the system. A few bugs were identified and fixed to get a satisfactory system. The cloud factory was rolled out with six business to business (B2B) partners to test the efficacy of the system. This gave us better inputs and provided some good inputs on user interfaces and fine-tune our pricing algorithm and more file type upload options. Figures 5, 6 and 7 show the digital interface screenshots.

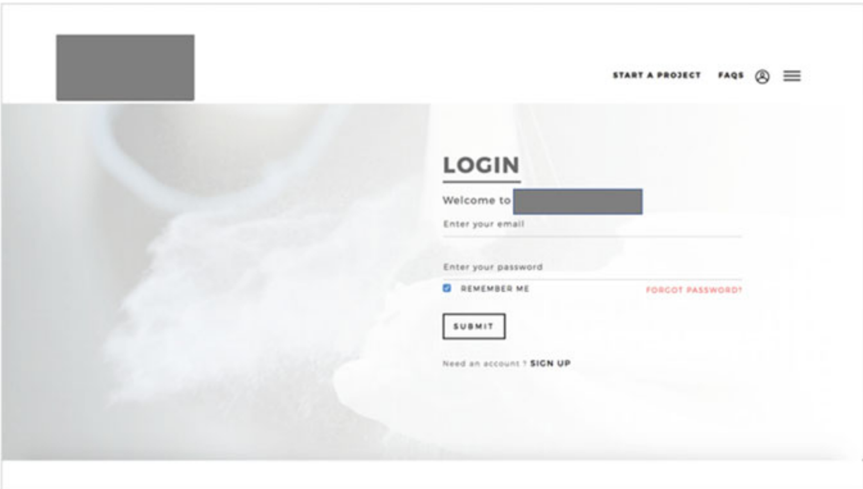

Fig. 5 The cloud factory login page www.imaginarium.io

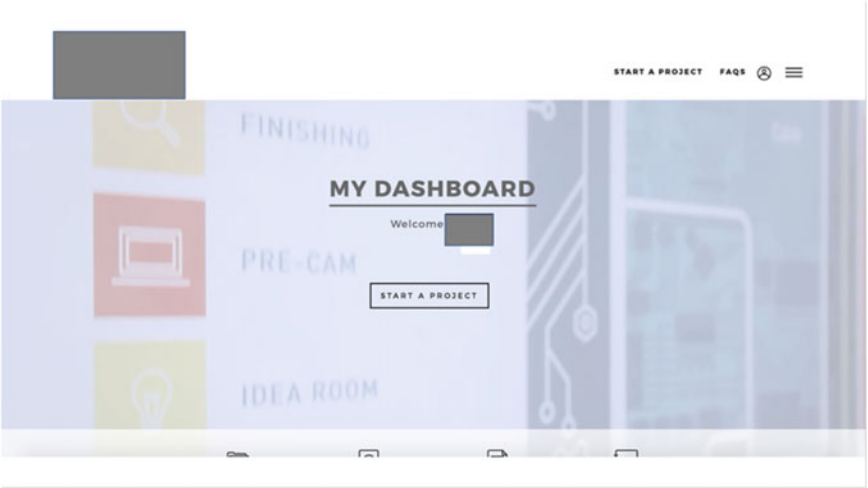

Fig. 6 The dash board to upload the file

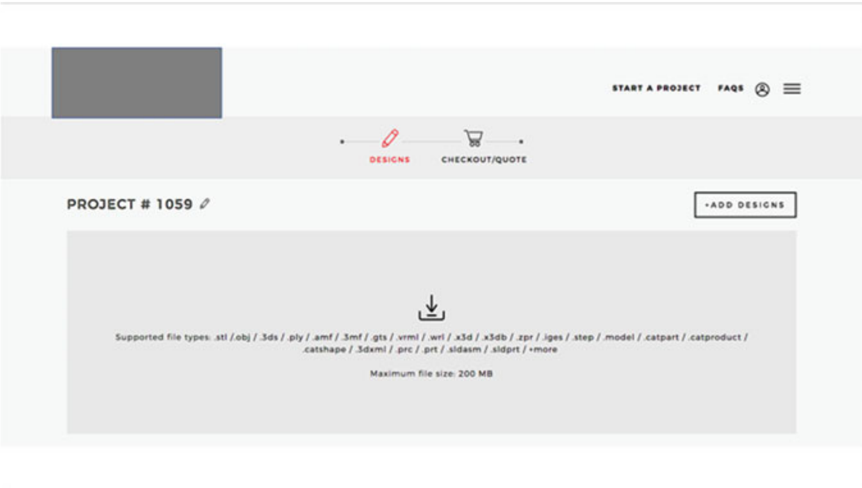

Fig. 7 The various file formats supported by the portal

5 Results and Conclusions

Since its launch, more than 12,000 orders have been successfully executed with 1000 plus happy customers. There were many repeat orders. And built while our phone customer care is still busy, the calls have come down.

A cloud factory model has been successfully designed, built and tested. From B2B, we will soon extend it to business to customer (B2C). We had many challenges we need to address such as

- **Standardization**

The services which are being offered by this system do not follow any standards which might create an issue if any customer raises serious concern over the calculating algorithm.

- **The Upload and Print Experience**

As we all know that 3D-printing provides freedom for designers to create complex shapes. This can lead them to design and print the product easily using their 3D-printers.

- **Product Timelines**

Online portal for order processing does have certain limitations with the timeline calculation algorithm. These limitations will not be able to provide an exact duration of time for a particular component to get fabricated using 3D-printing.

- **Storage**

Huge storage to be maintained on cloud along with security provisions to maintain the Intellectual Property Rights (IPR) of the customer. This storage size completely depends on the traffic which a cloud portal is handling.

- **Client Interface (CI)**

It usually works in a browser using WebGL technologies, and therefore, large models cannot be loaded as 3D objects within the browser. We solved this by putting a logic of loading images instead of 3D when the size of the 3D model is greater than 10 MB.

6 Limitations

- File Processing Algorithms

3D file processing is a serial CPU process, which requires huge CPU and RAM capabilities, so processing multiple complex 3D models on a single high-end server would also create resource bottleneck on a server and may freeze the operations. The dimensions, surface area and volume cannot help identify the complexity of the design, making pricing less accurate.

- Costing Evaluation

Accurate pricing for complex manufacturing processes like vacuum casting, injection moulding and CNC machining is not possible.

- Human Intervention

Role of human will always be critical even in cloud manufacturing.

- Processing Limits

Large complex models (>200 MB) cannot be processed.

- File Fixing

Copyrights of the 3D file uploaded cannot be validated while being processed, while there are great desktop software's available to do file fixing with high human intervention, the cloud file fixing cannot replicate the accuracy of 3D file fixing done with human manually in 3D desktop softwares (e.g. Magics, Netfabb).

7 Future Scope

1. Graphics processing unit (GPU) can play a great role in 3D file processing.
2. Artificial intelligence (AI) can be used to generate accurate pricing for complex processes.
3. With IoT, cloud systems will be even more smartly connected with machines to automate a lot of processes.
4. Cloud manufacturing platform can also become a collaborative tool for design communication.
5. Cloud companies can create software specific extensions, so manufacturing-related services can directly be availed from within the 3D design software.
6. Accurate pricing is a key to success in digital manufacturing, and to increase the accuracy of pricing, machine learning can be leveraged. For example,
   - 6.1. Pricing algorithms can be created with certain hypothesis of parameters and algorithms,
   - 6.2. Pricing generated by the system and later actual production data and the actual cost of producing the parts can be recorded,
   - 6.3. Both the data types can be processed with machine learning for making the algorithms better, and it can continue becoming better every day.
7. A large digital manufacturing company which produces thousands of parts each month can use the 3D model data and image processing technique to accurately predict the manufacturing cost of given part by identifying similar 3D models produced in past by searching through a database.
8. Machine learning can also be used to gather design data from patent offices and thereby helping and protecting against getting them copied through digital manufacturing's upload and print functionalities.

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Automated Tolerance Analysis of Mechanical Assembly Using STEP AP 242 Managed Model-Based 3D Engineering

O. V. S. Praveen, Bandaru Dileep, Satya Gayatri, K. Deepak Lawrence, and R. Manu

Abstract Tolerance analyses of mechanical assembly play a very crucial role as the accumulation of tolerance affects the functionality of the product in actual service conditions. There are various methods that can be applied to a mechanical assembly to perform tolerance analysis. With the advancement in computer technology and the advent of numerous CAD packages, there is a scope to automate the process of tolerance analysis. This paper is focused on the automation of tolerance analysis using STEP AP 242 Managed Model-Based 3D Engineering. An attempt to automate the process of tolerance analysis is reported in this paper for a mechanical assembly with GD&T using matrix method by means of a software module developed in Python.

Keywords Tolerance analysis · STEP AP242 file · GD&T · Matrix method

1 Introduction

Tolerance specification is a very important aspect in the design of mechanical components as exact production of a part according to the specified dimension and geometry is not possible. Hence, any mechanical design is incomplete without the specification of Geometric Dimension and Tolerance (GD&T). However, when the components

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A. Chakrabarti and M. Arora (eds.), *Industry 4.0 and Advanced Manufacturing*, Lecture Notes in Mechanical Engineering,
https://doi.org/10.1007/978-981-15-5689-0_14

are assembled, their individual tolerances accumulate to affect the functionality of the assembly. To account for this variability, tolerance analysis of the assembly is performed using various tolerance analysis methods. As the assembly becomes more and more complex, the complexity of the tolerance analysis algorithm also increases. Nevertheless, with the advent of CAD/CAM software, this computational effort has been considerably reduced. Over the years, there have been emerged a number of CAD packages with different file output formats. Hence, there is a need for a platform-independent CAD standard to carry out the analysis. STEP (Standard for Exchange of Product model data) file is a CAD file format used to share data of 3D models between users of different CAD formats. ISO TC 184 developed STEP that describes standardized data models in several application protocols (AP). STEP AP 242 contains computable representations for several types of 3D model data such as dimensioning, tolerancing, mating rules, surface texture, material specifications and other similar information known as Product Manufacturing Information (PMI). STEP AP242 is introduced with an intent to automate the manufacturing functions such as tolerance analyses, fixture design, CNC code generation and generation of inspection plans for the quality control during various phases of product realization.

2 Literature Review

Desrochers and Riviere [1] developed a tolerance analysis using the matrix method and demonstrated the technique for two meshing gears of a gear pump assembly. Marziale and Polini [2] applied the matrix model for an assembly of a rectangular frame with two discs. Chen et al. [3] compared various types of tolerance analysis models, namely matrix model, unified Jacobian–Torsor (UJT), direct linearization method (DLM) and tolerance mapping. Davidson et al. [4] developed the concept of T-Maps for the tolerance analyses which is in accordance with ISO standards of GD&T. Feeney et al. [5] describe the capabilities of STEP AP 242 in handling tolerance information associated with product geometry, and how these capabilities enable the manufacturing systems to be smart. The main intent of STEP file is to support a manufacturing enterprise with a range of standardized information model that flows through a long and wide ‘digital thread’ that makes the manufacturing systems in the enterprise smart. STEP AP 242 is an efficient way for handling tolerance information associated with product geometry because it merges both AP 203 and AP 214 which were earlier used separately by aerospace and automobile industries, respectively. The main advantage of step file is 2D drawings can be replaced by 3D models with annotations and semantics which are machine-readable. STEP file analyser developed by National Institute of Standards and Technology (NIST) for the extraction of GD&T information from a STEP AP242 file [6]. Model-based definition (MBD) of the product means the three-dimensional computer-aided design (CAD) models that contain geometry, topology, relationships, attributes and features that are necessary to completely define the component part or assembly of parts for the purpose of design, manufacturing, analyses, testing and inspection. These concepts are detailed in ISO 16792 (2015) which is adapted from ASME Y14.5 [7]. The model-based enterprise (MBE) uses model-based definition (MBD) as a way to transition away from using traditional paper-based drawings and documentation [8]. From the literature review, it is observed that there is a paucity of work that makes use of STEP files for automating the tolerance analyses of mechanical assemblies with GD&T data. This work makes an attempt to extract the MBD data from the STEP AP242 file by means of STEP Analyser. A Python script is developed to extract the required GD&T data for performing tolerance analysis using matrix method.

3 Methodology

The approach proposed for automated tolerance analysis of a mechanical assembly begins with a 3D modelling of the assembly in CAD software that supports the AP242 file format. The overview of the approach is briefly represented in Fig. 1.

3.1 CAD Model and GD&T Extraction from STEP AP242 File

After modelling an assembly in a CAD software (Autodesk Inventor in the present work), it is exported as STEP AP242 file. STEP AP242 is written in EXPRESS schema, and it must be extracted in proper human interpretable model. For this NIST STEP File Analyser, a software developed by NIST is used. The output of the NIST STEP File Analyser is an Excel file with several sheets corresponding to different entities defined in the 3D CAD model. From that Excel file, all the GD&T information is extracted using a Python script and copied to another spreadsheet.

The Python code used can be accessed on GitHub through the following link: https://github.com/ovspraveen/GD-T-Extraction.git.

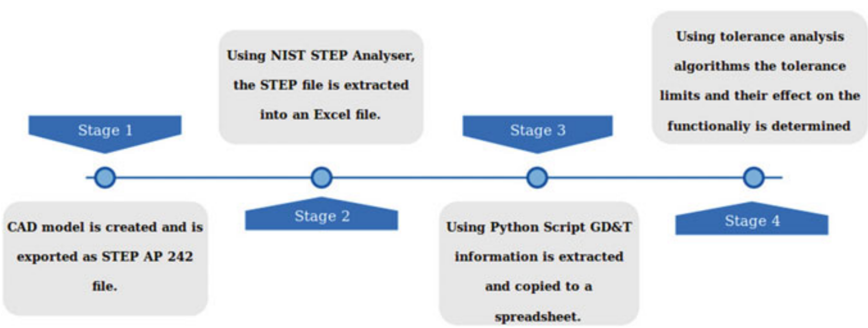

Fig. 1 Proposed approach for automatic tolerance analyses

The code is run on Jupyter Notebook running on Ubuntu 14.04.4 LTS operating system.

The following pseudocode describes logic of the code:

```
Start

Input section

    input "STEP excel SHEET" into WB

Processing section

    len=number of sheets in workbook
    Loop i from 0 to len-1
         Read sheet from WB at i
         Remove first 2 lines and NULL rows from all
sheets

#Seperating GD&T data

         Read "PMI Representation Summary" sheet
into df
         Add columns "Dimensions" and "Tolerance" to
the sheet
         Split Dimension and Tolerance values
         Copy Dimension values to Dimensions column
         Copy Tolerance values to Tolerance column

Output section

#Copying GD&T data to excel file

        Copy Dimensions and Tolerance values to a
DataFrame
          Save values to sheet "test"

End
```

3.2 Tolerance Analysis Using Matrix Model

The extracted GD&T information is fed as an input to the matrix method for tolerance analyses to obtain the minimum and maximum value for tolerance limits. The resulting objective function with constraints obtained from the matrix method is solved using the GRG non-linear algorithm available in Excel solver.

4 Case Study

The above approach for automated tolerance analysis is applied to an assembly of the rectangular frame and two discs that are reported in the literature [2]. The representation of the assembly model is shown in Fig. 2. The complete GD&T defined model is created using Autodesk Inventor, and the STEP AP242 file is extracted. Tolerance analysis is performed by matrix method.

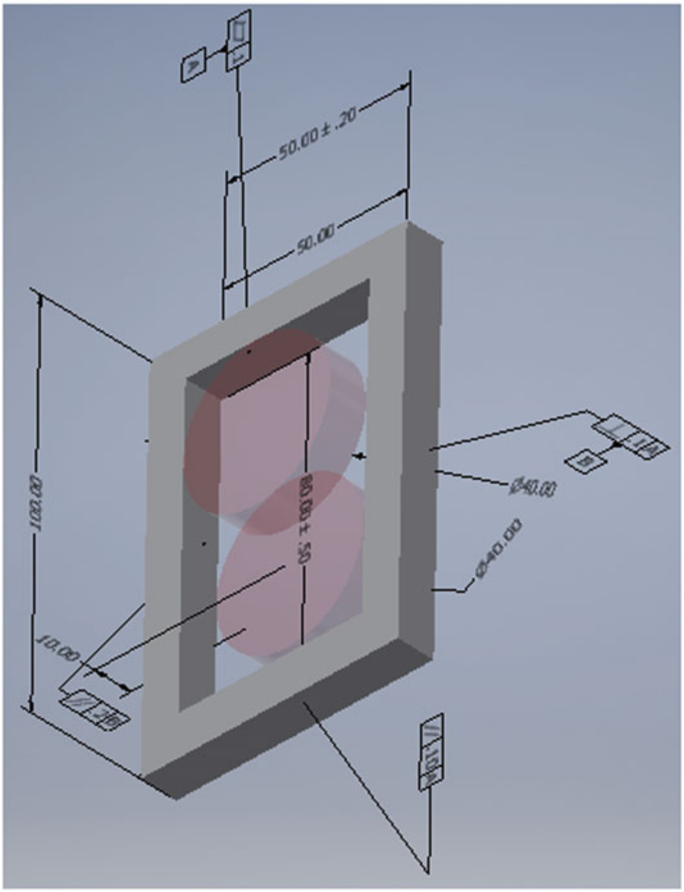

Fig. 2 3D CAD model with fully defined GD&T

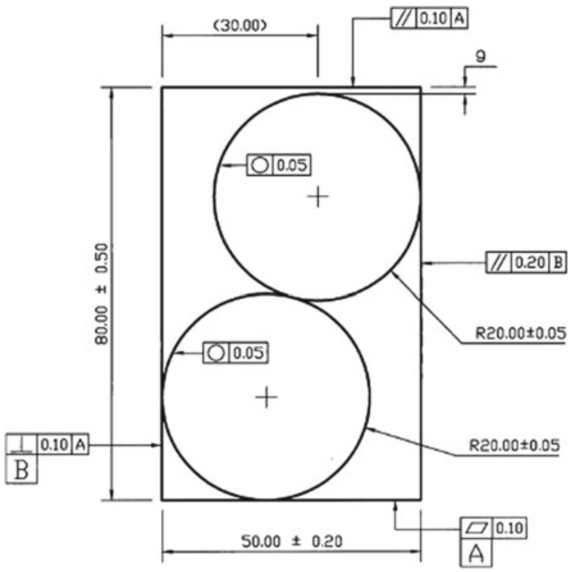

Fig. 3 2D drawing of the assembly showing the clearance to be determined (*Source* Adv. Manuf. Technol. 43, p. 78)

4.1 Tolerance Analysis

The objective of the tolerance analysis model is to determine the final clearance '*g*' after the assembly of parts as shown in Fig. 3. Matrix method of tolerance analyses is used for this purpose.

4.1.1 Matrix Model

The main objective of the matrix model is obtaining extreme limits for a distance function by developing objective function from the tolerances assigned on each feature in the assembly with constraints developed from extreme limits of each tolerance zone [1]. Matrix model uses the displacement matrix D represented in Eq. 1, where the generalized displacement matrix is the product of six elementary displacements, namely three translational and three rotational

$$D = \begin{bmatrix} C\gamma C\beta & -S\gamma C\alpha + C\gamma C\beta S\alpha & S\gamma S\alpha + C\gamma S\beta C\alpha & u \\ -S\gamma C\beta & C\gamma C\alpha + S\gamma S\beta S\alpha & -C\gamma S\alpha + S\gamma S\beta C\alpha & v \\ -S\beta & C\beta S\alpha & C\beta C\alpha & w \\ 0 & 0 & 0 & 1 \end{bmatrix} \quad (1)$$

where α, β, γ small rotational displacements, u, v, w are small translational displacements and $C\,\alpha$ corresponds to the cosine of angle α and $S\,\alpha$ corresponds to the sine of angle α. When this generalized matrix is modified by setting zero to those elements which are invariant, it provides the displacement matrix corresponding to a class of the surface.

For a cylindrical surface, translational displacement along its own axis, i.e. *u,* and also rotational displacement about its own axis, i.e.α are invariant. Thus, by equating $\alpha = 0$, $u = 0$ gives the displacement matrix corresponding to cylindrical surface feature as represented by Eq. 2.

$$D = \begin{bmatrix} C\gamma C\beta & -S\gamma & C\alpha S\beta & u \\ -S\gamma C\beta & C\gamma & S\gamma S\beta & v \\ -S\beta & 0 & C\beta & w \\ 0 & 0 & 0 & 1 \end{bmatrix} \quad (2)$$

For each feature to which tolerance is applied, there is a local datum reference frame (DRF) and a displacement matrix that is defined with respect to the local DRF. The displacements calculated from individual local references are transformed into a chosen global reference frame using transformation matrices. The next step is to draw an assembly graph in which each semicircle represents part and arrows connecting them indicate corresponding tolerance associated with the features [2]. Then, the required objective function is obtained from the assembly graph by moving in a particular direction and accumulating individual tolerances. Once objective function and constraints are developed, these are solved for their extreme values and the difference between two extreme values gives the required tolerance value. For the assembly shown in Fig. 2.

$$\text{Objective Function: } Y_f - \left(Y_{E,R\_5} + Y_{E,R\_2} + Y_{E,R\_4} + Y_{E,R\_6}\right)$$

where Y_{E,R_i} is the variability of local datum reference frame of corresponding *i*th feature.

With the following constraints

- $-0.5 \le u_3 - 25 * \sin\gamma_3 \le 0.5$
- $-0.5 \le u_3 + 25 * \sin\gamma_3 \le 0.5$
- $-0.1 \le 50 * \sin\gamma_3 \le 0.1$
- $-0.05 \le v_5 \le 0.05$
- $-0.05 \le u_5 \le 0.05$
- $-0.05 \le 0.25 * u_5 + 0.97 * v_5 \le 0.05$
- $-0.2 \le u_{2-4}\ 0 * \sin\gamma_2 \le 0.2$
- $-0.2 \le u_2 + 40 * \sin\gamma_2 \le 0.2$
- $-0.2 \le 80 * \sin\gamma_2 \le 0.2$
- $-0.05 \le u_6 \le 0.05$
- $-0.05 \le v_6 \le 0.05$
- $-0.05 \le 0.25 * u_6 + 0.9682 * v_6 \le 0.05$
- $-0.01 \le 80 * \sin\gamma_4 \le 0.01$

where

u_i is the small displacement in X—the direction of feature L_i,
v_i is the small displacement in Y—the direction of feature L_i,
γ_i is the rotational displacement of feature L_i.

The detailed mathematical explanation for arriving at the constraints is explained in appendix of Ref. [2].

The CAD model is exported as STEP AP242 format. NIST STEP File Analyser is used to extract information from STEP files into an Excel file. The Python script is used to copy the GD&T data to perform tolerance analysis using standard optimization algorithms in Excel. The objective function along with constraints that are shown above is solved, and the minimum limit for the clearance is found to be 0.14 mm and maximum limit at 0.55 mm. Hence, there is a tolerance limit of ±0.69 mm. The entire chain of events for the tolerance is performed automatically except the use of Excel Solver where constraints are to be manually entered.

5 Conclusion

The new era in manufacturing is digital and smart. Smart manufacturing systems are enabled by 3D model-based engineering in which a digital 3D model serves as the core information source for all activities in the product lifecycle. The manufacturing is moving away from paper documentation and drawings and approaching information models that are machine-readable. 3D models with Geometrical Dimensioning and Tolerancing (GD&T) and Functional Tolerancing and Annotations (FT & A) are swiftly substituting 2D-based production drawing as the master artefact for product development and manufacturing. Tolerance analysis provides an insight into the effects of individual part tolerance on the overall functionality of the assembly. This paper discusses an approach towards the automation of tolerance analysis process by means of the STEP AP242 file. Matrix model is used as an algorithm to carry out tolerance analysis. The proposed approach for tolerance analysis is demonstrated by presenting a case study of a mechanical assembly with fully defined dimensional and geometric tolerances.

The inimitability of this work is to incorporate the use of STEP file data of an assembly as input for tolerance analysis. Moreover, the existing automated tolerance analysis methods that are available with the current CAD packages give the result based on plus-minus tolerance analysis or root square sum method. In these methods, usually form tolerance is not taken into account. Under the proposed methodology matrix method, the tolerance analysis also takes into account the form tolerance of the given assembly.

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Assembly Management Software Integrated with Additive Manufacturing for Micro, Small, and Medium Enterprises

Arun Baby, B. C. Saeed Rila, G. K. Anil Vishnu, and Hardik J. Pandya

Abstract Part tracking is an important module of Enterprise Resource Planning (ERP) software. For a conventional (non-automated) micro, small, and medium enterprise (MSME) manufacturer, implementing part tracking is one of the vital components for improving product quality. This paper explains about the features and functionality of the developed software which integrates part tracking, remote 3D printing, and assembly assistance.

Keywords Part-tracking software · Assembly line · Remote 3D printing · I4.0 · Material management

1 Introduction

The Enterprise Resource Planning (ERP) and part-tracking software are exclusively used in manufacturing industries. There is a lot of manufacturing plants which do not use smart manufacturing and resource planning technologies. The automated tracking in the assembly line improves the overall efficiency of the plant and production quality [1, 2].

Internet of things (IoT) is popular in consumer electronics. The German government describes a combination of technologies to make factories automated [3]. The campaign by the German government is called Industry 4.0 or I4.0. I4.0 is a cyber-physical system which consists of smart machines, production, and storage systems which are connected to allow automatic information exchange and decision making [3]. Implementation of smart manufacturing techniques in the manufacturing sector will boost production quality and quantity [4].

Industrial robotics, cybersecurity, Internet of things, cloud computing, cloud storage, additive manufacturing, artificial intelligence, big data, virtual reality, and

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A. Chakrabarti and M. Arora (eds.), *Industry 4.0 and Advanced Manufacturing*, Lecture Notes in Mechanical Engineering,
https://doi.org/10.1007/978-981-15-5689-0_15

augmented reality will be the main areas and techniques used for the implementation of I4.0. These areas will clock the highest growth rate compared to other manufacturing areas in India and other Asian countries like China, Japan by 2025 [5].

The Indian manufacturing industry is one of the most promising sectors for implementing I4.0. It contributes 15–16% of national GDP and around 12% of the working population employed this sector. However, the extent of implementation of I4.0 technologies across different sectors is different [5].

For the implementation of the image-based automated part/assembly scanning, the image quality of the captured barcode is important. The image quality of the barcode will depend on the camera, camera angle, lighting technique, lighting angle, etc. [6]. In this research work, we present software developed in-house which is generic and can be used to track parts/assemblies with any scanning technologies such as barcodes, data matrix codes, and RFID.

2 Software Architecture

2.1 Overview

The software architecture for assembly management is shown in Fig. 1. The software helps the user to tag parts using a barcode, summarize the inventory, interact with a 3D printer, and assist in assembly, testing, and packaging. The parts at each station are logged along with the printer telemetry into a cloud database.

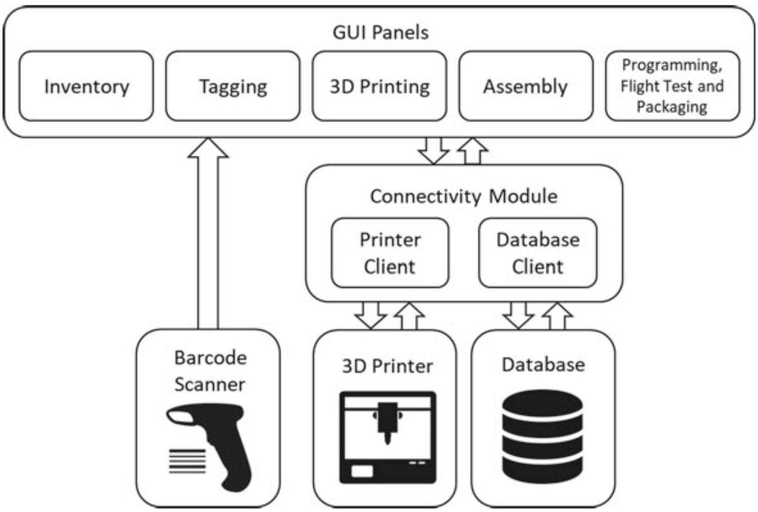

Fig. 1 Schematic of the assembly management software architecture

The software consists of a graphical user interface (GUI) panels, connectivity module, hardware interface, and a cloud database. The hardware consists of a barcode scanner and 3D printer which can print the parts associated with the part being scanned at a given point-of-time. The GUI deals with the frontend of the software which interacts with the user. It is implemented in Swing toolkit [7]. The connectivity module deals with all the application programming interfaces (APIs) used to communicate with the hardware and the cloud database.

2.2 GUI Panels

We have designed and implemented GUI panels for inventory tagging (Fig. 2), inventory summary, part scanning, and information (Fig. 3), 3D printing interface (Fig. 4), assembly assist (Fig. 5), and final checklists for the application/assembly (case study: semi-automated assembly lines for drones) (Fig. 6).

For the semi-automated assembly lines for drones, the following steps are used: (a) the inventory panel deals with inventory summary and individual part detail information. Barcodes with a serial number are generated with Code 128 standard (ISO/IEC 15417:2007), using free online barcode generating tool. The barcodes are then printed on barcode label paper. The barcodes are attached to all the incoming parts in the inventory. The part is then tagged/logged into the inventory database when the "Tag" button is pressed. It is then inspected, based on which the operator can mark the "tagged" part as pass or fail, along with remarks in the GUI. All the parts in the inventory are thus logged into the database. The part name, type, and QA result are the main parameters entered to the database for each part. (b) The next GUI panel is

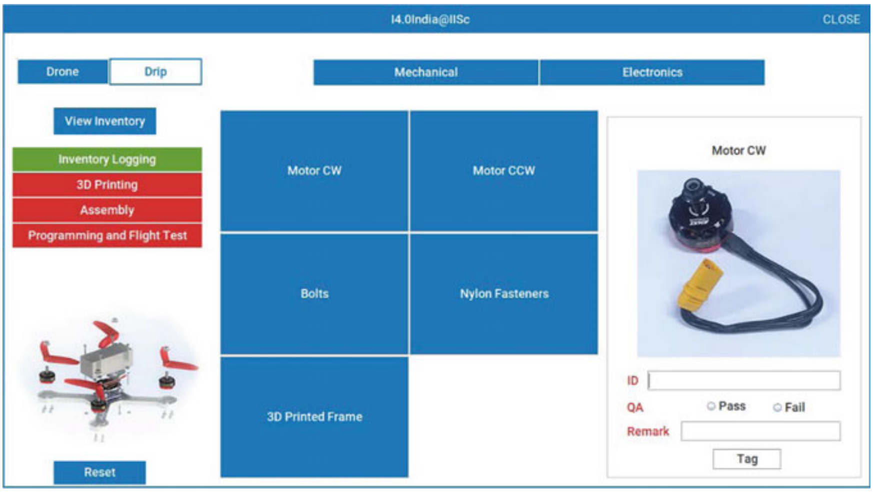

Fig. 2 GUI panel for inventory logging

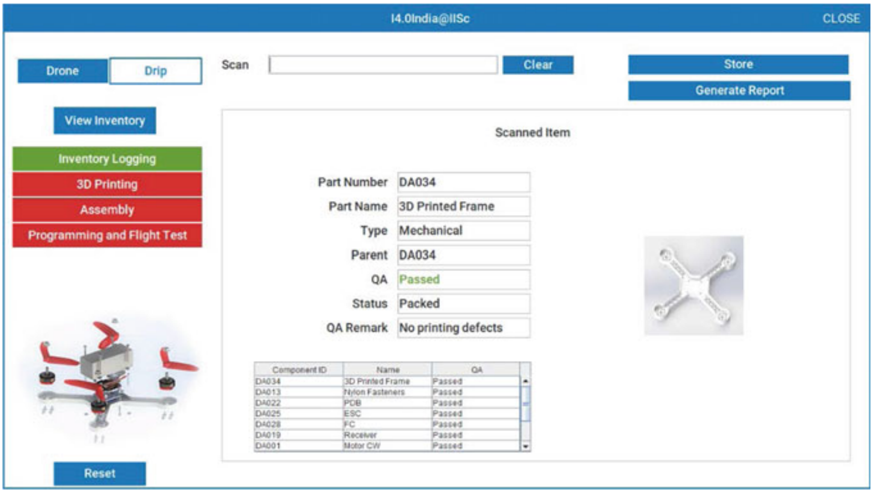

Fig. 3 GUI panel for viewing the inventory

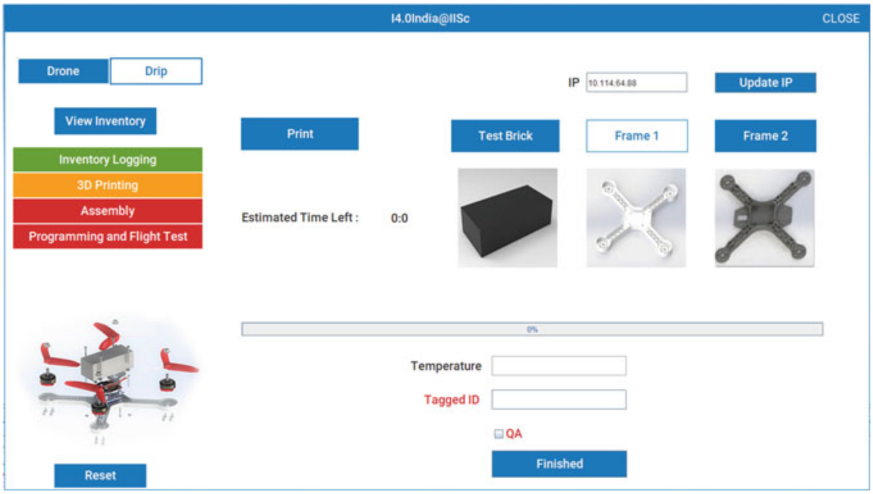

Fig. 4 GUI panel for 3D printing

the 3D printer panel. It handles 3D printer commands and shows print progress along with nozzle temperature. Users can select the object that needs to be printed. Once the print is completed, the part is inspected, barcoded, and tagged into the database. (c) In the assembly panel, instructions to assemble are given with photographs of the parts. The user scans only the item shown in the present instruction. The GUI will not register the component if it is not the one mentioned in the given instruction. Hence, manual errors in the assembly are reduced. (d) Finally, the last panel checks if the

Fig. 5 GUI panel for assembly

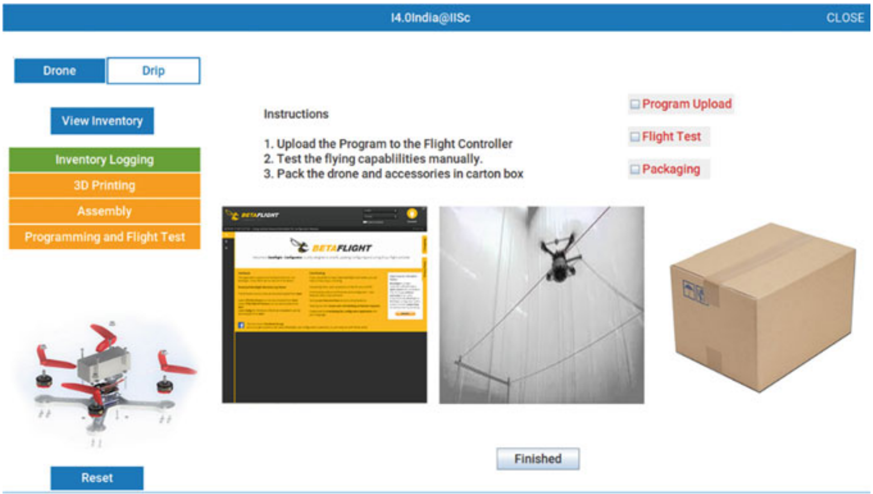

Fig. 6 GUI panel for programming and flight test

assembly is programmed, tested, and packaged. The user can track at what stage the components are from the inventory. All the programming of the GUI is done using Java.

2.3 Connectivity Module

This module interfaces I4.0 technologies with the software. The data logging is carried out onto a CosmosDB database in Microsoft Azure [8]. The resource is accessed via a MongoDB API. For the purpose of additive manufacturing, a 3D printer is used. The printer is controlled via an Octoprint server [9]. Octoprint is an open-source controller for 3D printers. Access to the printer is carried out through a Representational State Transfer (REST) API. The REST API provides inter-operability between computers on the Internet [10]. The telemetry is logged into the Azure database for further analysis.

3 Result

The proposed system is implemented for drone assembling as a case study. The parts and sub-assemblies of drones are tagged using a GUI panel for inventory logging (Fig. 2). The GUI has a feature to view logged part summary and details about the parts (Fig. 3). The frame is 3D printed (Fig. 4), tagged, and logged onto the database. The assembly check is also performed using the same GUI (Fig. 5). Instructions are provided for final programming and testing (Fig. 6), thereby providing an end-to-end solution from inventory management, product printing, and assembly assistance. Additionally, users without prior knowledge in assembling a drone were asked to perform the above tasks. Since the images corresponding to each component and instruction were given, they could easily tag the right components and assemble the drone with the instructions given in the GUI.

The tagging was completed in 8 min. The command is given from the GUI to a 3D printer to print the right frame for the drone. A 3D printer is situated on a remote location and connected to the same LAN as that of the GUI, thus enabling remote printing. Printing took 5 h making it as the bottleneck. The assembling task was completed within 30 min. Because of the intuitive user interface, the time taken from inventory logging till the testing is reduced significantly.

4 Discussion

The system implements material and process management in a much smaller yet focused manner. It is unique in integrating inventory management, real-time additive manufacturing, tagging and logging, and assembly assistance into a single application. Since we are using cloud computing, the constraints associated with scaling are limited. Further work needs to be carried out to produce a more generic GUI in which the user can have enhanced control over the process flow. Use of barcodes limits the size of the parts that can be tracked through this system. Alternatives to barcodes need to be explored and integrated with this system. Though 3D printer took the longest time, it requires minimal human intervention. Hence, the focus is required to fully automate the 3D printing setup in a robust manner. This can eliminate the bottleneck by having multiple printers running 24 $\times$ 7 without any human intervention. In addition to that, interfaces to other manufacturing processes such as CNC machining, automated-guided vehicles (AGVs) for transfers can be added as extra nodes which could be configured for each assembly. Implementation of such cost-effective software with GUI will help a lot of micro, small, and medium enterprises in their overall production management. Since the present system is tested in a laboratory environment, we envisage further validation of the system by deployment in an industrial setting.

Acknowledgements The authors would like to acknowledge insights shared by Mr. Venu Allam, and the financial support received from Industry 4.0 @IISc.

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Materials Processing and Joining

Application of Design for Additive Manufacturing to an Automotive Component

R. Sakthivel Murugan and S. Vinodh

Abstract Additive manufacturing plays an important role in the modern era for fabricating complex geometry with less wastage. It has the ability to manufacture complex geometry product at low cost and less weight. The design of product for achieving the former-said objective is termed as design for additive manufacturing (DFAM). It is achieved by several design guidelines. In this paper, five DFAM guidelines are followed to make the product with less weight, less material and low printing time. DFAM methods like topology optimization and lattice structure generation are focused to reduce component's material with high stiffness. DFAM methods like design by direct assembly, build orientation and support reduction are implemented to reduce printing time and material volume. All these five DFAM methods are well suited for extrusion-based additive manufacturing technique, and it will help design engineers to create lightweight components in automobile, aerospace and electronics application.

Keywords DFAM · Additive manufacturing · Lightweight components · Topology optimization · Lattice structure

1 Introduction

Several researches are going on to make lighter products in automobile, aerospace, biomedical components, etc., in order to optimize its cost and material usage. It is difficult to produce using traditional manufacturing process due to its shape complexity and complex geometrical profile. Hence, additive manufacturing (AM) plays a vital role here, and it could be adopted to achieve the requirement. The factors affecting AM are printing time, cost and material volume. In order to print

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A. Chakrabarti and M. Arora (eds.), *Industry 4.0 and Advanced Manufacturing*, Lecture Notes in Mechanical Engineering,
https://doi.org/10.1007/978-981-15-5689-0_16

large assemblies or components, there exist requirement to design the parts with low weight, less material and less printing time. These are achieved through design for additive manufacturing (DFAM) concepts along with DFAM guidelines.

The major opportunities, constraints and economic considerations were presented for design for additive manufacturing and its relevant design or redesign for AM production [1].

A novel methodology was proposed for the weight reduction of Messerschmitt–Bolkow–Blohm (MBB) beam with perfect strength-to-weight ratios using topology optimization (TO) [2]. Topology optimized part was printed in FDM process using the proposed methodology. CAD model was built with adaptive cellular structure using square and circular holes which was refined with TO parts.

A guide to principle to rule (GPR) approach was proposed to describe and categorize the design rule, design principle, design fundamental and design guidelines [3].

The design for cellular structures was proposed using two approaches. The first one by DFAM is used for modelling, process planning and manufacturing simulation and the second one by manufacturable elements (MELs), an intermediate support for manufacturing-related problems [4].

The design rules were framed to minimize material, printing time and cost using DFAM guidelines by avoiding overhang structure, modifying infill patterns and horizontal holes [5]. Topology optimization was done by solid isotropic material with penalization (SIMP) methodology using COSMOL Multiphysics software [6]. Part was produced using FDM by reducing the total strain energy and increases the stiffness and mechanical properties.

AM part was redesigned using DFAM methods. Process-driven shape and designer-driven shape DFAM methods were adopted to improve the performance and to reduce print cost and time [7].

The design rules were addressed for designing and fabricating large and complex components for FDM [8]. The design guidelines were applied, and the results with various FDM nozzles, build orientations and strength considerations are compared.

The topological design and optimization, meta material construction of the critical part, various ways to program variations in form and performance of the topology study were applied in the study [9].

The objective of the paper is to study and apply DFAM methods to an existing component in automotive field. It aims to redesign of the component using DFAM methods with reduction in printing time, material, weight and printing cost.

In this paper, five DFAM Methods were applied to make the lightweight product with less material and to produce it through FDM technique in less printing time. This could really help the design engineers, researchers and industrial practitioners for getting an industry ready product through DFAM in short time.

2 DFAM Methods

There are several DFAM methods suggested in Thompson et al. [1]. In this paper, five major DFAM methods were focused to improve the design of additive manufacturing part. They are as follows.

(1) Topology optimization
(2) Direct printing of assemblies
(3) Design by build orientation
(4) Support structure reduction
(5) Design by lattice structure.

2.1 Topology Optimization

Topology optimization is an optimization technique for reducing the material in a structure with applied boundary conditions to yield a better shape using CAE software. The manufacturing of the resulted topology optimized parts is only possible with AM. This methodology for the preparation of AM parts using topology optimization was developed to optimize its mass by material removal [10]. The optimization goals are the one which selects the algorithm based on certain objectives like best stiffness-to-weight ratio, minimizing mass and minimizing maximum displacement. The solvers run the algorithm at the background with number of iterations to get the optimized results with safe design of stress values.

2.2 Direct Printing of Assemblies

In AM, the printing of individual parts would take more time for printing. It includes machine calibration time, time for heating of nozzles, platform movement time, nozzle movement time, support nozzle movement time, nozzle changing sensor control response time, cleaning of nozzle tip time and actuation system responses time. All time delays are due to the configuration of stepper motors, belt drive frictions, capacity of the heating units and microcontroller response with integration to the system. A comparative study was made about AM part consolidation and individual multi pieces assembly [11]. Hence, if the printing was directly done with assemblies, it could save more printing time and printing cost. This could be achieved by designing the assembly of the entire parts with proper clearance and orientation using any CAD software package.

2.3 Design by Build Orientation

The printing of products with various orientation results in varying printing time, material and support material usage and printing cost. It all depends on the generation of support layer creation, raster filling and contour layer generation. By selecting the proper build orientation with suitable design guidelines, it would be easier to achieve the objectives with proper design constraints. The design by build orientation includes the design of narrow structure from printing bed to avoid support layer generation, avoidance of overhang structure and bridge structure, design of holes normal to the printing nozzle, design of structures with optimized height to reduce the number of layers built.

2.4 Support Structure Reduction

DFAM component aims to reduce the entire structure with less requirement for support structure. Support structure development in printing stage absolutely makes increment in the printing time and cost. There are certain design guidelines to design the component with less requirement for support structure. It includes design by proper overhang structures, inclination angle of 45° or less from vertical axis of build layer and holes in orthogonal build direction. Also, support structure removal process is quite complex in certain complicated structures which results in breakage or structural deformation in that component. The design of structure at the base should be flat to get full contact on the printing bed to reduce support material usage.

2.5 Design by Lattice Structure

Lattice structure is a predefined connective structure with a unit cell. The lattice structure design is not only for lightweight structure but also for high stiffness design. The lattice structure is hard to design manually. Some CAD packages have defined algorithm for lattice structure generation within the mentioned volume. A comprehensive review of the state-of-the-art design methods for additive manufacturing (AM) technologies in lattice structure design was idealized to improve its functional performance [12]. The support structure and printing time may be quite high. The removal of support structure is tedious, and it needs some post processing techniques. Anyway, this DFAM technique aims to produce only lightweight structure with high stiffness.

3 Case Study

Case studies are used to demonstrate the proposed methodologies and compare the results to highlight the benefits and limitations of the parts fabricated using FDM. DFAM guidelines were also applied in the snap fit joints to demonstrate its possibility and strength [13]. Thermal properties of Pin fin Heat Sink using topology optimization with DFAM guidelines were compared for its air cooling [14]. However, in the existing literature, mostly single design guideline was implemented and compared for its optimal results. If multiple design guidelines were implemented in a part, then it needs to be further optimized for industry ready product with less cost and high stiffness.

In this paper, car interior door handle assembly was taken as a case study for DFAM. Figure 1 shows the car interior door handle for a car model. It is used to open the car left door from the interior. The component is made up of plastic material.

Some DFAM techniques were used for this door handle, and the results were discussed for its printing time, material volume and support material volume. The design improvements are discussed for each design guidelines.

3.1 CAD Modelling and FEA Analysis

3D CAD modelling for the car interior door handle is shown in Fig. 2 was done in SolidWorks 2018 software. The entire design was benchmarked, and the dimensions are retrieved by standard measuring techniques. Then, 3D modelling and assembly were done with proper features. The initial mass and volume of the door handle component were 10.38 g and 10,135 mm^3.

Also, finite element analysis was done to check the safety aspect of design by applying the load. The static stress analysis was performed in ANSYS 18 Workbench software. The load applied on the downward surface of the handle and the constraints on the hole where the spring is used. The material used in both modelling and analysis is ABS plastic, and the properties are listed in Table 1.

Fig. 1 Car interior door handle

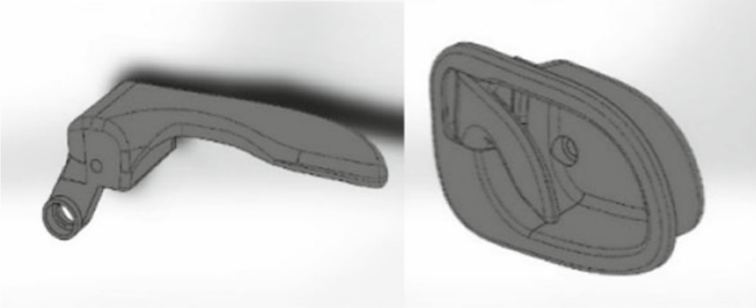


Fig. 2 CAD modelling of car interior door handle

Table 1 Properties of ABS material

Young's modulus MPa	Poisson's ratio	Bulk modulus MPa	Shear modulus MPa
2000	0.394	3144.7	717.36

Figure 3 shows results of the displacement and von Mises stress plot of static stress analysis which was done by using ANSYS Workbench. The results are listed in Table 2. The yield stress of ABS plastic was 40 MPa. The maximum stress applied is 29.596 MPa. Therefore, it will not undergo any deformation in real time, and the design is safe.

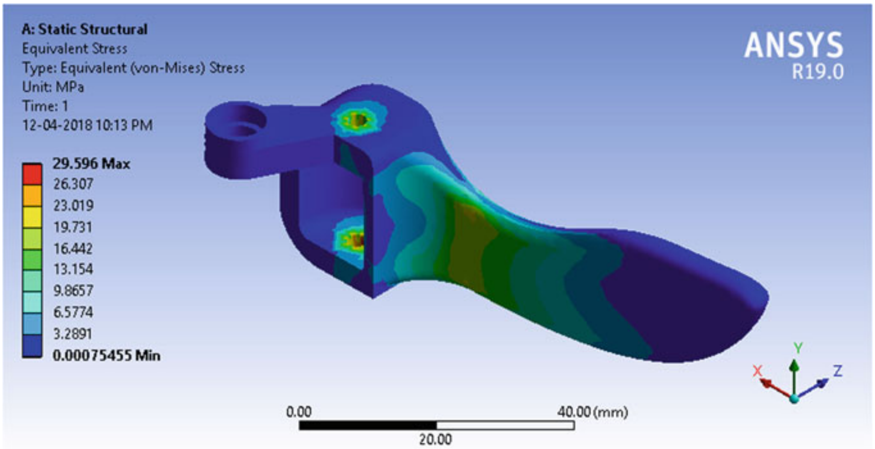


Fig. 3 Von Mises plot of handle

Table 2 Simulation results of car handle in ANSYS Workbench

S. No.	Particulars	Min	Max	Avg
1	Total deformation plot	0 mm	5.157 mm	0.83842 mm
2	Von Misses stress	7.5455e−004 MPa	29.596 MPa	3.2048 MPa

4 Results and Discussions

Various results of five DFAM methods are carried out and are presented in this paper. The printing time, material volume and support volume are calculated using GrabCAD Print software. It is a slicing software recommended for UprintSE Plus Stratasys FDM Printer. The results are discussed below.

4.1 Topology Optimization

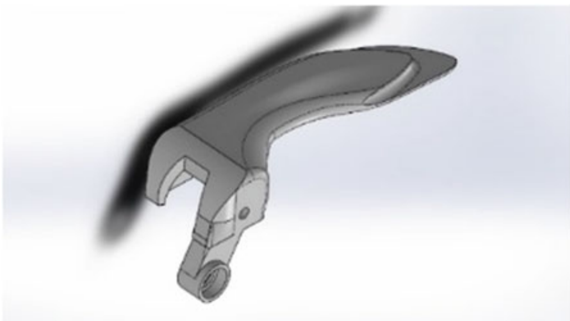
Topology optimization was done on car interior door handle using SolidWorks Simulation software. The design guidelines are applied for the reconstruction of the new car handle based on topology optimization results. Figure 4 shows the reconstructed 3D CAD model of car door handle based on topology optimization.

Figure 5 shows von Mises stress plot of newly reconstructed car interior door handle part which was completed by static stress analysis using ANSYS Workbench. The results are listed in Table 3. The maximum stress applied is 31.608 MPa which is less than the yield stress, and therefore, it will not undergo any deformation in real time, and the design is safe.

The two interior door handles as shown in Figs. 2 and 4 are printed in FDM UPrintSE Plus printer by using its respective .stl files. The printing data are shown in Table 4.

It is noted that there is a reduction of 6.60% in printing time, 17% in model material and 2.5% in support material when compared to that of topology optimized car handle parts. Hence, DFAM by topology optimization at last attains good result.

Fig. 4 Reconstructed CAD model based on TO



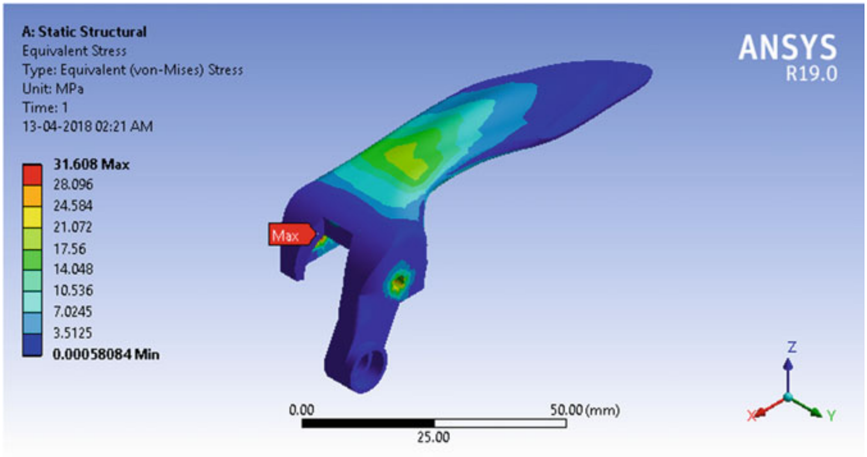


Fig. 5 Von Mises stress of TO car handle

Table 3 Simulation results of topology optimized reconstructed car handle

S. No.	Particulars	Min	Max	Avg
1	Total deformation plot	0 mm	5.2891 mm.	0.80177 mm.
2	Von Mises stress	5.8084e−004 MPa	31.608 MPa	3.3704 MPa

Table 4 Results of printing data by DFAM for topology optimization

S. No.	Particulars	Print Time (min)	Model Material (in^3)	Support Material (in^3)
1	Car interior handle	106	0.577	0.193
2	Topology optimized car interior handle	99	0.476	0.188
	Change in percentage (%)	−6.60	−17.50	−2.59

4.2 Direct Printing of Assemblies

The interior door handle assembly consists of two individual parts. One is the door handle, and the other is its hub as in Fig. 6. If one part is printed and the next part in printing sequence leads to long printing time, more model material and support material usage. Hence, direct printing of assembly of both parts at the same time will improve the printing time and materials. It is achieved by changing the printing settings in slicing software Grab CAD. Similarly, direct assembly printing of topology optimized part will lead to further improvement in printing parameters.

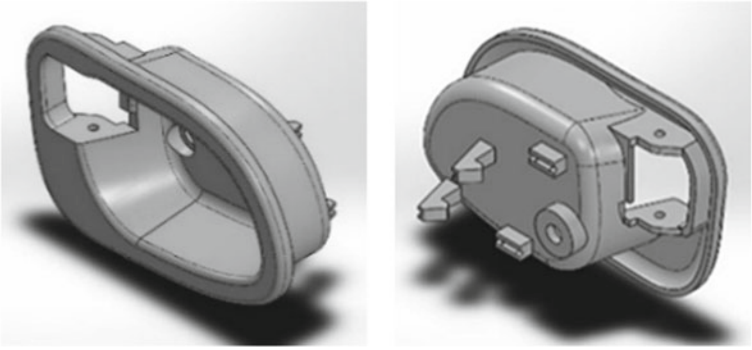


Fig. 6 3D model of interior door handle hub

Table 5 Results of printing data by DFAM through printing direct assemblies

S. No.	Particulars	Print time (min)	Model material (in^3)	Support material (in^3)
1	Car interior handle-part 1	119	0.568	0.472
2	Car interior handle-part 2	256	1.94	1.45
3	Printing by direct assembly	322	2.488	1.57
4	Total time for printing two parts	375	2.508	1.922
	Change in percentage (%)	−14.13	−0.79	−18.31

Table 5 represents the printing statistical data of each individual part and in assembly state.

It shows that there is reduction in 14% of printing time, 0.8% of model material and 18% of support material while print by direct assemblies when compared to that of printing the same component as individual parts. Also, it could take some more additional time for developing the assembly manually. Hence, DFAM of direct assemblies not only made some improvements in printing data and also in emission control, energy utilization.

4.3 Design by Build Orientation

Build orientation is printing the component by varying its rotational degrees of freedom in all the *x*-, *y*- and *z*-axis. It could be varied from 0° to 360°. In this case study, four major orientations are considered, namely horizontal, side, bottom and vertical. Figures 7, 8, 9 and 10 represent the build orientation by horizontal, side,

Fig. 7 Horizontal BO

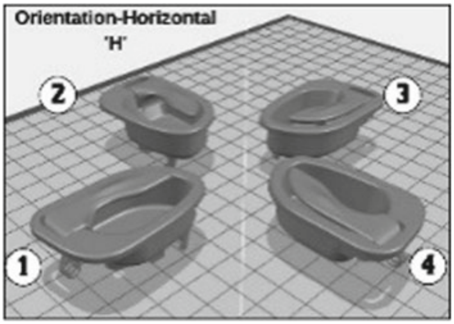


Fig. 8 Side BO

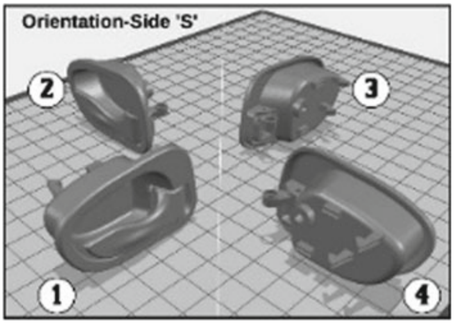


Fig. 9 Bottom BO

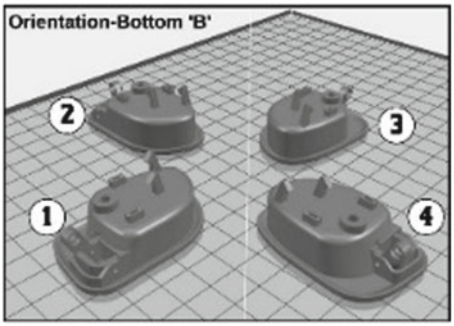


Fig. 10 Vertical BO

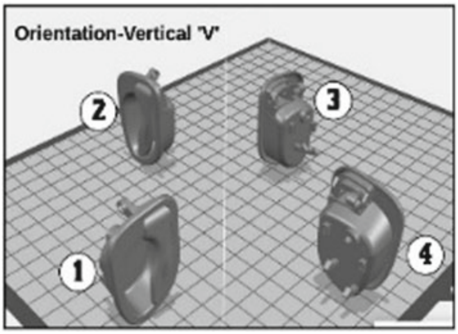


Table 6 Results of printing data by varying its build orientation for printing direct assemblies

S. No.	Part No.	Print time (min)	Model material (in^3)	Support material (in^3)	Average print time (min)	Average model material (in^3)	Average support material (in^3)
1	H1	322	2.488	1.57	324.25	2.4875	1.6945
2	H2	323	2.487	1.729			
3	H3	327	2.488	1.75			
4	H4	325	2.487	1.729			
5	S1	439	2.453	1.779	438.25	2.454	1.782
6	S2	438	2.456	1.779			
7	S3	440	2.453	1.804			
8	S4	436	2.454	1.766			
9	B1	304	2.474	1.234	304.25	2.47375	1.23625
10	B2	304	2.474	1.241			
11	B3	305	2.474	1.236			
12	B4	304	2.473	1.234			
13	V1	504	2.502	1.666	501	2.5	1.6365
14	V2	500	2.5	1.608			
15	V3	493	2.498	1.562			
16	V4	507	2.5	1.71			

bottom and vertical. Each orientation has four printed samples with each having 90° variation in counterclockwise direction. Totally, 16 samples were studied for the DFAM using build orientation. Table 6 represents the printing data of all the 16 samples by varying its build orientations.

From the results, it has been observed that each build orientation has different printing data. The bottom orientation has the optimized values in all the parameters when compared with all other orientations. Bottom orientation has reduction of 39.27% of printing time, 1.05% model material and 24.45% support material when compared with vertical orientation.

4.4 Support Structure Reduction

DFAM for support structure reduction aims to design the part or assembly with less utilization of supports. Support structure reduction was done for the interior car door handle assembly by making the contact surface of the part with the print bed as flat without having any gap. Support structure reduction was done for the interior car door handle assembly by making the contact surface of the part flat with the print bed without having any gap. This gap between the part and the print bed is designed

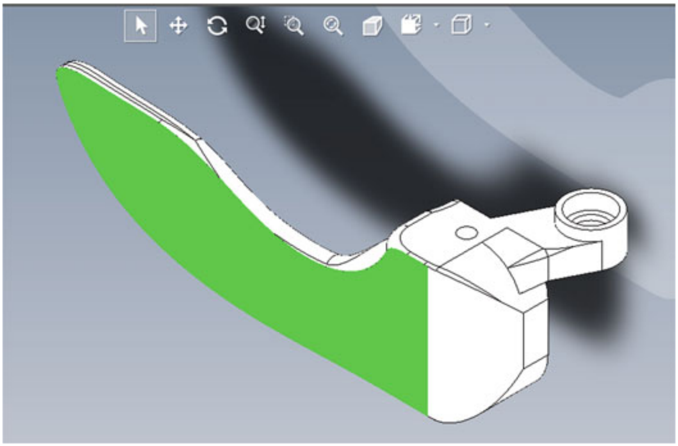


Fig. 11 Design for support structure

Table 7 Results of printing data of DFAM by support reduction

S. No.	Particulars	Print time (min)	Model material (in^3)	Support material (in^3)
1	Car interior handle	125	0.574	0.334
2	DFAM by support reduction	98	0.461	0.299
	Change in percentage (%)	−21.6	−19.68	−10.47

to be eliminated in order to remove the support structure. Figure 11 represents the remodel of the car door handle by making one of the sides as flat for the reduction of support material.

Table 7 shows the printing data of DFAM by support material reduction. It shows that there is reduction of about 21.6% in printing time, 19.6% of model material and 10.5% of support material by using DFAM technique when compared to the initial design.

4.5 Design by Lattice Structure

Lattice structure creation for the case component was achieved by using Materialize Magics software. Some pre-processing works were done in Magics software for stl file correction, shell conversion, triangulation error correction, edge correction, etc. The structure used for the development of lattice structure isrhombic dodecahedron and diamond. Both structures had 20% relative density with the structure unit cell

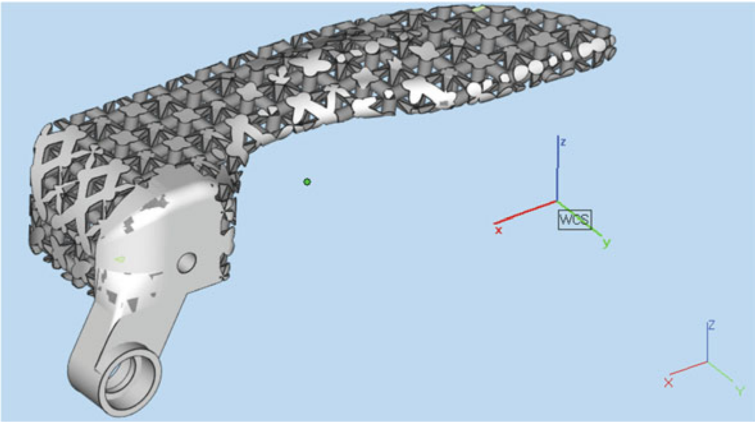


Fig. 12 Design of lattice structure

Table 8 Results of printing data of DFAM by support reduction

S. No.	Particulars	Print time (min)	Model material (in^3)	Support material (in^3)
1	Car interior handle	125	0.574	0.334
2	DFAM using lattice structure component	213	0.314	0.454
	Change in percentage (%)	70.4	−45.30	35.93

dimension of 10 mm. Figure 12 shows the lattice structure of car door handle part. It has low weight structure but with high stiffness.

Table 8 shows the printing data of DFAM by lattice structure generation. It shows that there is reduction of about 45% in model material volume and increase of 70.4% of printing time and 35.93% of support material when compared to the initial design. Thus, DFAM of lattice structure not only reduces the weight and also maintains the strength and rigidity of the components.

4.6 Discussions

Topology optimization was implemented in the part with the objective of weight reduction and high stiffness. However, the mass is reduced by 8% within the yield strength. By direct printing of assemblies, the part could be printed in less time with proper joints. This could be achieved by making certain clearance in the joints. By printing a part with particular build orientation, around 39% of printing time could be optimized. However, there are various strategies for the reduction of support material, and this case study focussed on removal of complex smooth surfaces over the handle to flat surface. Though, design by lattice structure takes so much time for post processing in the removal of support structure yet it creates the part with less weight with high stiffness.

These five design guidelines could be applied to all automotive plastic parts which are subjected to less force boundary conditions. These design guidelines have certain limitations in terms of dimensional accuracy, surface roughness, support material removal rate, design guideline implementation knowledge to the designers and material limitations, etc. But these five guidelines can be a good optimizer for any automotive industry pertaining to plastic parts.

5 Conclusion

Five DFAM methods using topology optimization, build orientation, direct assemblies, support reduction and lattice generation were used to create lightweight components with less material usage in less time. An automotive component of interior door handle assembly was considered as a case study component. The implications if adopting DFAM guidelines include the reduction in printing time, material usage and printing cost on the redesigned case component when compared to the initial design. The redesigned component using topology optimization, lattice generation had von Mises stress within the yield stress, and hence, the redesign is perfectly safe. Later on, it will be printed in bottom orientation by direct assembly to get further optimized product. These five DFAM methods are well opted for extrusion-based additive manufacturing and also for any automotive component. By implementing these guidelines sequentially, the final redesigned automotive component can be optimized around 11.20% in printing time, 80.32% in material usage and 19.89% in support material usage.

There are certain limitations in printing size of components, support removal process with topology optimization and lattice structure generated components, surface finish and some distortions in the components using DFAM. In future, DFAM results are verified with experimentation results. Apart from five DFAM methods, some more DFAM methods like design by part consolidation, design for mass production, design for FDM machine capabilities, design of overhangs and bridges, etc., will also be implemented to any component for its improved design in future.

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Fabrication of Single and Dual Adhesive Bonded Lap Joints Between Dissimilar Composite Adherends

R. Jairaja and G. Narayana Naik

Abstract Composite materials like Carbon Fiber Reinforced Plastics (CFRP) and Glass Fiber Reinforced Plastics (GFRP) are increasingly used in aircraft structure due to high specific strength and specific stiffness. In this work, CFRP and GFRP laminates have been fabricated using hand layup and vacuum bagging techniques, then the fabricated CFRP and GFRP laminates are cut into the required dimensions and are used as dissimilar composite adherends to construct the composite lap joints. The designed mould is used to fabricate the single and dual adhesive bonded lap joint specimens using AV138 brittle and Araldite-2015 ductile adhesives between dissimilar composite adherends (CFRP and GFRP) according to ASTM D 5868 standard. X-ray radiography testing has been carried out to assess the quality of the specimen. Uniaxial tensile tests have been conducted to obtain the single and dual adhesive bond strength. From the study, it is found that the use of dual adhesives helps in increasing the bond strength between the dissimilar composite adherends.

Keywords Composite materials · Adhesive bonded joints · CFRP · GFRP

1 Introduction

Joints are required to construct the entire structure in all fields of engineering and non-engineering applications. Joints are the critical locations in the structure because loads transfer through the joints between the parts within the assemblies and sub-assemblies in the structure, if the joints are not properly constructed, then the loads concentrate around the joints and forms the stress concentrations resulting in premature failure of the structure. In conventional joints like bolted or riveted joints requires initial drilling of holes in the adherends, which introduces the localized stress concentrations around

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A. Chakrabarti and M. Arora (eds.), *Industry 4.0 and Advanced Manufacturing*, Lecture Notes in Mechanical Engineering,
https://doi.org/10.1007/978-981-15-5689-0_17

the hole and weakens the surrounding materials, and then insertion of bolt-nuts or rivets adds weight. However, drilling of composite adherends is not recommended because fiber damage and delamination near the hole occurs.

The CFRP and GFRP are the most commonly used composite materials in aircraft structure because of excellent specific stiffness and specific strength, joining of these two materials are essential for structural optimization. Adhesively bonded joints are becoming favored joining options to join similar and dissimilar composite materials. Adhesive bonding of aircraft structures [1], review of the strength of joints in FRPs [2], Overview of adhesively bonded joints in composite materials [3], an updated review of adhesively bonded joints in composite materials [4]. These studies described that adhesive bonds are increasingly used to join the composite materials and permits to construct lightweight structures that are highly beneficial in the aircraft industry. Nevertheless, the strength of the adhesive-bonded joint is low compared to bolted or riveted joints and bond strength mainly depends on the type of adhesives used. Therefore, strengthening of the adhesive bond is an essential requirement to improve the performance and life of the structure. Adhesives play an important role in the joining of composite joints and sometimes there is a need to use a combination of adhesives to achieve better bond strength. In this work, an attempt has been made to use the individual and combinations of the AV138 brittle and Araldite-2015 ductile adhesives in the bonded regions between the dissimilar composite adherends.

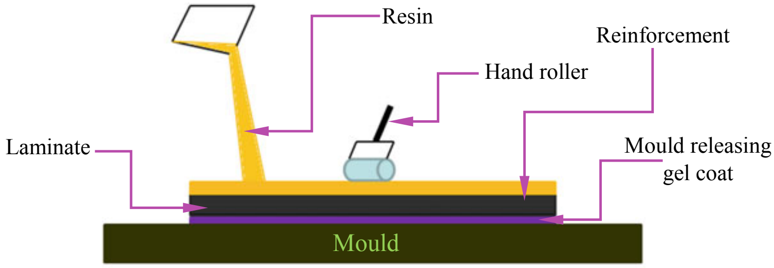
2 Manufacture of Composite Laminates

The manufacture of composite laminates is a complex process and depends on various parameters such as reinforcement material, matrix types, volume fractions, component geometry and tooling requirements.

Fiber-reinforced plastics (FRP) are used significantly to improve the performance of the structures in various applications. Placing and retaining of fibers in a particular direction is important and provides specified strength and stiffness for specific applications. Hand layup and vacuum bagging technique are the oldest and perhaps the simplest method to manufacture the FRPs. Schematic representation of hand layup and vacuum bagging technique is illustrated in Fig. 1. In this work, CFRP and GFRP laminates have been fabricated using hand layup and vacuum bagging methods, which are explained in the following subsection.

2.1 Fabrication of CFRP and GFRP Laminates

The CFRP laminate of dimensions $400 \times 400 \times 2.5$ mm have been fabricated using hand layup and vacuum bagging techniques. Unidirectional carbon fabric eight layers of 300 GSM with epoxy resin (LY556/HY 951) having a volume fraction of 60:40 used to fabricate the CFRP laminate and the detailed fabrication process is explained



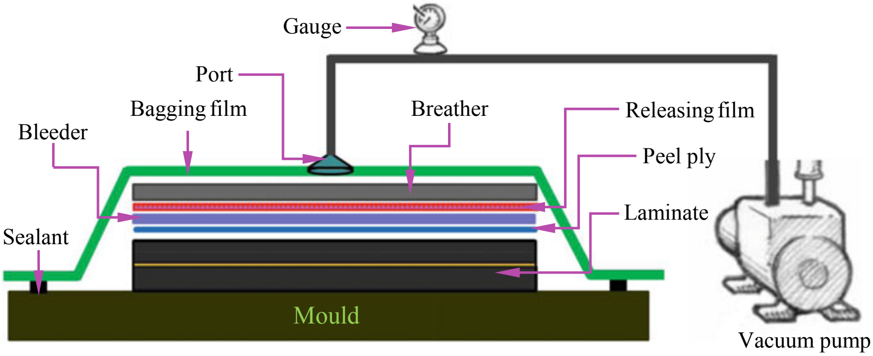


Fig. 1 Schematic display of hand layup and vacuum bagging method. **a** Hand layup method. **b** Vacuum bagging method

in Fig. 2. All the carbon layers are stacked in 0° direction. The vacuum pressure of 7 bar is applied using vacuum bagging technique to hold laminate plies together and the laminate is cured at laboratory room temperature for 24 h.

The GFRP laminate of dimensions 400 × 400 × 2.5 mm have been fabricated using hand layup and vacuum bagging techniques. Unidirectional glass fabric 200 GSM of 12 layers with epoxy resin (LY556/HY 951) having a volume fraction of 60:40 used to fabricate the GFRP laminate and the detailed fabrication process is explained in Fig. 3. All the glass fabric layers are stacked in 0° direction under vacuum pressure. The GFRP laminate is cured at laboratory room temperature for 24 h.

3 Manufacture of Composite Joints

The thickness of CFRP and GFRP laminates are measured using digital vernier caliper at different locations and the variation is 2.46–2.54 mm but most of the

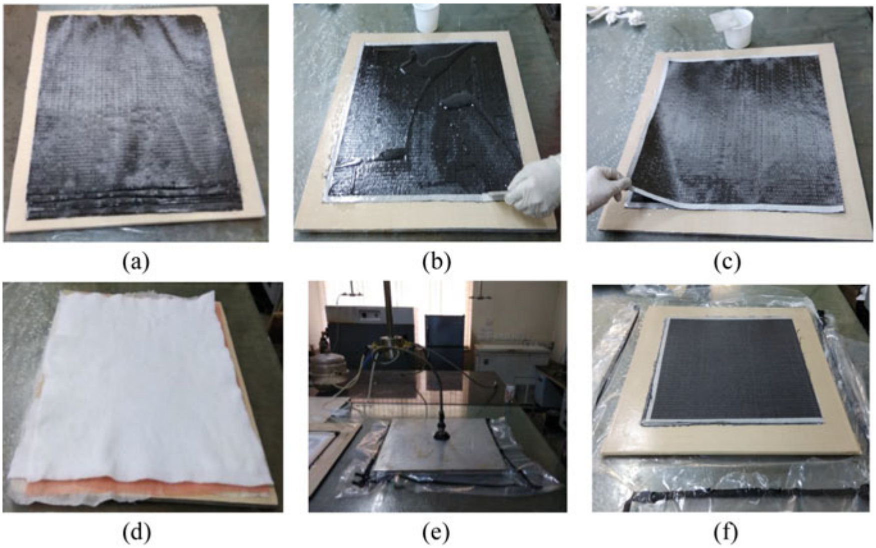


Fig. 2 Detailed fabrication process of CFRP laminate: **a** UD carbon fiber layer eight numbers, **b** Applying epoxy and hardener mixture, **c** Stacking of UD carbon fiber lamina, **d** Placing of peel ply, releasing film and breather material for vacuum bagging process, **e** Curing of CFRP laminate under vacuum pressure and **f** Vacuum bag opened after curing

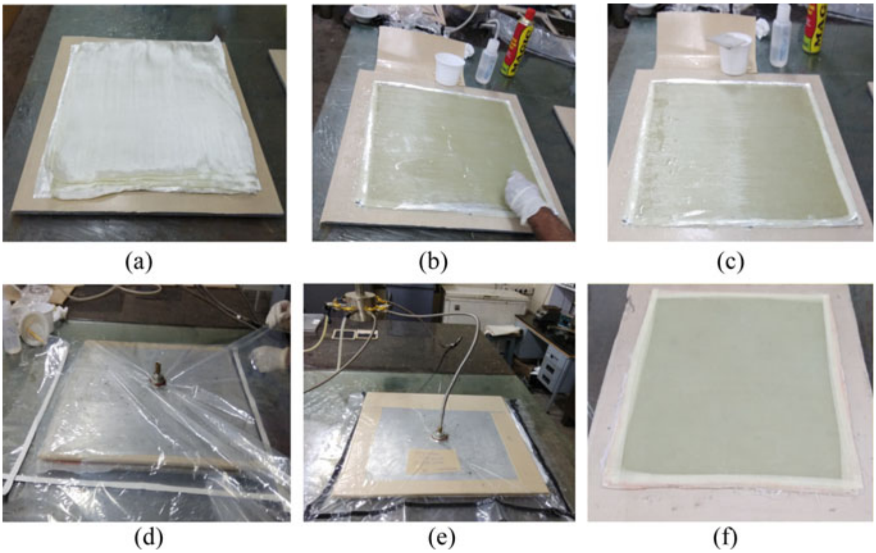


Fig. 3 Detailed fabrication process of GFRP laminate: **a** UD glass fiber lamina 12 numbers, **b** Applying epoxy and hardener mixture, **c** Stacking of UD glass fiber lamina, **d** Preparation of vacuum bagging, **e** Curing of GFRP laminate under vacuum pressure and **f** GFRP laminate obtained after curing

Table 1 Type of single and dual adhesive bonded joint specimens

Specimen	Type of adhesive-bonded joints
S1	Single adhesive bonded joint using adhesive AV138
S2	Single adhesive bonded joint using adhesive Araldite-2015
S3	Dual adhesive bonded joint using adhesives Araldite-2015 at the edges and AV138 at the center 20% of the bonded length
S4	Dual adhesive bonded joint using adhesives Araldite-2015 at the edges and AV138 at the center 40% of the bonded length

location is 2.5 mm. Then CFRP and GFRP laminates have been cut into the required sizes 101.6 mm × 25.4 mm with the help of water jet machining.

Surface preparations are required on the bonding surfaces and that governs the bond strength to some extent [5]. The surface preparations have been carried out on the adherends bonding surfaces prior to adhesive bonding as per ASTM D 2093 standard [6]. The adherends bonding surfaces are cleaned and wiped with acetone using a fresh cloth to remove the impurities, markings and other contaminants. Sanding has been done on the adherends mating surfaces to create surface roughness using fine-grit emery cloth and then sanding particles are removed with fresh dry cloth. In polymer composites, sanding is used just to remove the surface of the resin without affecting fibers because epoxy surface bonds well with other epoxy adhesives, no chemical modifications are necessary. The bond strength depends on the material, geometry, surface treatment and environment [7]. Four different single and dual adhesive bonded joint specimens have been prepared as per ASTM D 5868 standard [8] and the corresponding specimen details are tabulated in Table 1. The geometrical configurations of four different single and dual adhesive bonded joint specimens are shown in Fig. 4.

In single adhesive bonded joints (S1 specimen and S2 specimen), the AV138 brittle and Araldite-2015 ductile adhesives are used in the bonded regions. Whereas, in dual adhesive bonded joints (S3 specimen and S4 specimen), both AV138 brittle and Araldite-2015 ductile adhesives are used as separate portions in the bonded regions. AV138 brittle adhesive is used in the middle of the bonded region at different dimensions and Araldite-2015 ductile adhesive used at the ends of the overlap because of high shear and peel strength. The vacuum degassing technique is used to remove the entrapped air in the adhesives during joint preparation prior to adhesive bonding. Adhesive-bonded joint specimens have been fabricated with the help of a designed mould. The detailed fabrication process of single adhesive lap joint specimens is explained in Figs. 5 and 6. Mould is cleaned and wiped with acetone using a fresh dry cloth to remove the impurities as shown in Figs. 5a and 6a. The GFRP adherends are aligned and placed properly in the mould as shown in Figs. 5b and 6b. The AV138 brittle and Araldite-2015 ductile adhesives are applied to the bonding region as shown in Figs. 5c and 6c.

In dual adhesive bonded joints due to different specific gravities of the two adhesives, brittle adhesive in the middle portion of the bonded region has a tendency

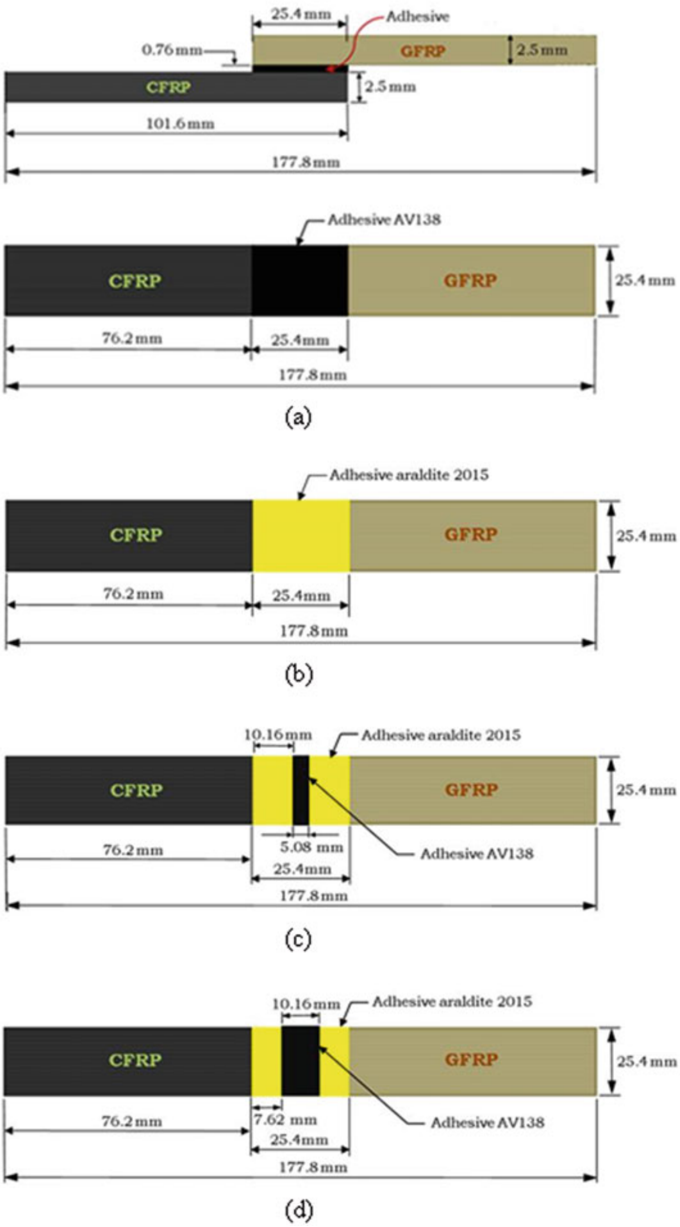


Fig. 4 Geometrical configurations of single and dual adhesive bonded joint specimens: **a** S1 specimen, **b** S2 specimen, **c** S3 specimen and **d** S4 specimen

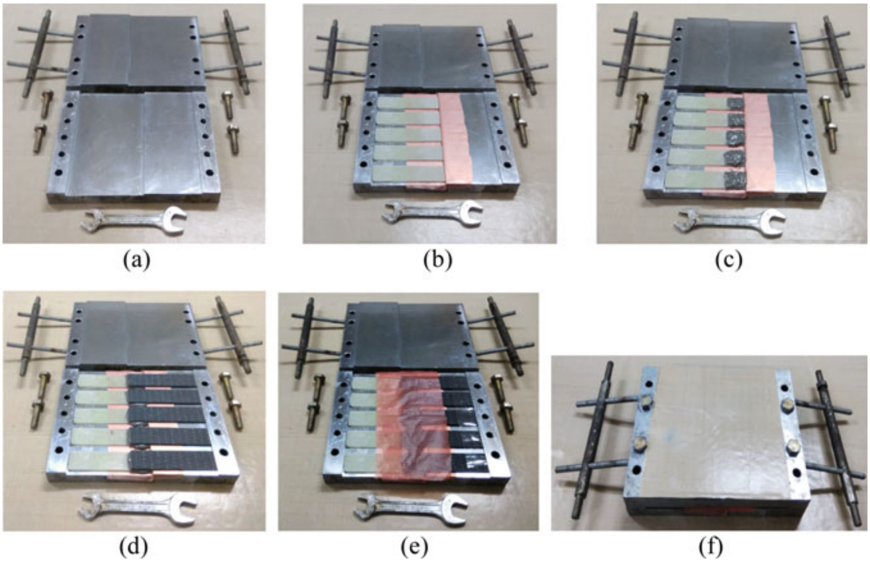


Fig. 5 Details about fabrication of single adhesive bonded joint S1 specimen: **a** Mould to create joints, **b** GFRP adherends are placed in the mould, **c** AV138 brittle adhesive applied in the bonded region, **d** Positioning of CFRP adherends, **e** Bonded regions are covered with releasing film and **f** Mould closed for adhesive curing

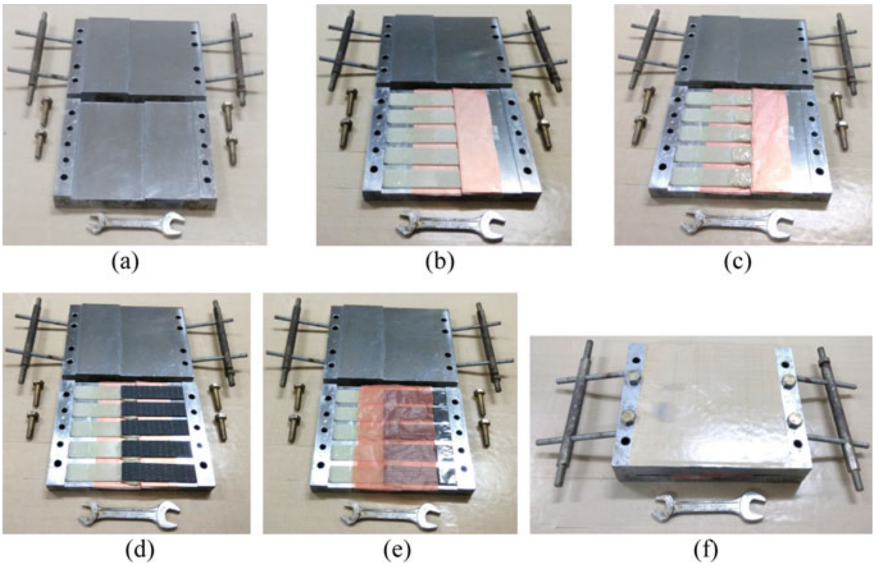


Fig. 6 Details about fabrication of single adhesive bonded joint S2 specimen: **a** Mould to create joints, **b** GFRP adherends are placed in the mould, **c** Araldite-2015 ductile adhesive applied in the bonded region, **d** Positioning of CFRP adherends, **e** Bonded regions are covered with releasing film and **f** Mould closed for adhesive curing

to squeeze-out the ductile adhesive or vice versa [9]. In this work, trial and error method has been adopted to maintain the dimensions of the adhesives in the dual adhesive bonded joint specimens. Proper marking has been done on the adherends in the bonded region and the masking tape has been used to cover the ends of the overlap as shown in Figs. 7a and 8a.The AV138 brittle adhesive has been applied at the center of the bond region and then Teflon tape has been removed when the brittle AV138 adhesive starts solidifying in the initial period of curing as shown in Figs. 7b and 8b. Then the Araldite-2015 ductile adhesive applied in the remaining area of the bonded regions at the ends of the overlap as shown in Figs. 7c and 8c. The releasing films are used in the mould around the bonded region as shown in Figs. 5d, 6d, 7d and 8d to avoid sticking of extra squeezed-out adhesive to the mould during curing. Then, the mould is closed tightly and placed in the oven at 70 °C for 24 h due to this, curing of adhesives occurs at faster rates and avoids direct mixing of adhesive in dual adhesive bonded joint specimens. This designed mould maintains a uniform bond line thickness of 0.76 mm. Five specimens are fabricated for each batch and all geometric configurations of the joints are selected as mentioned in the ASTM D 5868 standard.

The excess adhesives squeezed-out from the joints at the time of curing in the mould and the specimens having extra squeezed-out adhesives are shown in Fig. 9. The adhesive AV138 appears dark grey in colour (Fig. 9a) whereas adhesive Araldite-2015 is beige in colour (Fig. 9b). In simple visual inspection, it is easy to identify the

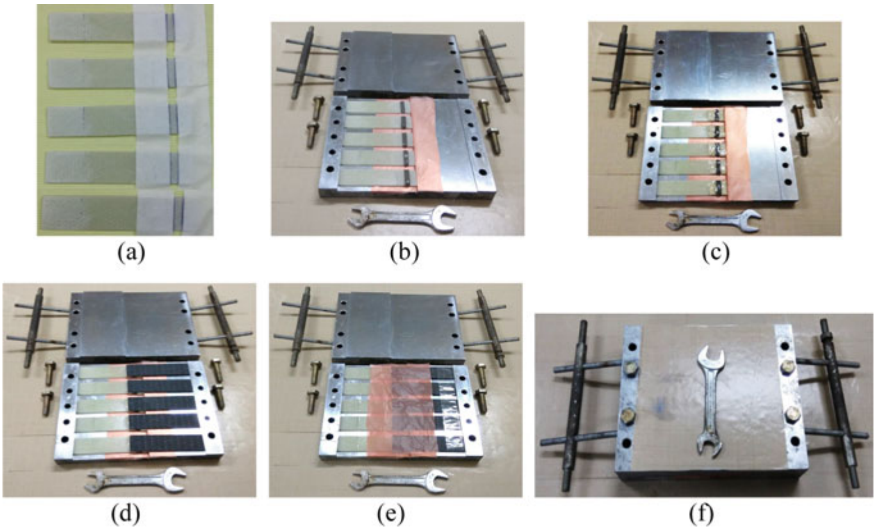


Fig. 7 Details about fabrication of dual adhesive bonded joint S3 specimen: **a** Ends of the overlaps are covered with mask tap, **b** GFRP adherends are placed in the mould with portion (20% of the bond length) of AV138 brittle adhesive at center of the bond, **c** Araldite-2015 ductile adhesive applied at the ends of the bonded regions, **d** Positioning of CFRP adherends, **e** Bonded regions are covered with releasing film and **f** Mould closed for adhesives curing

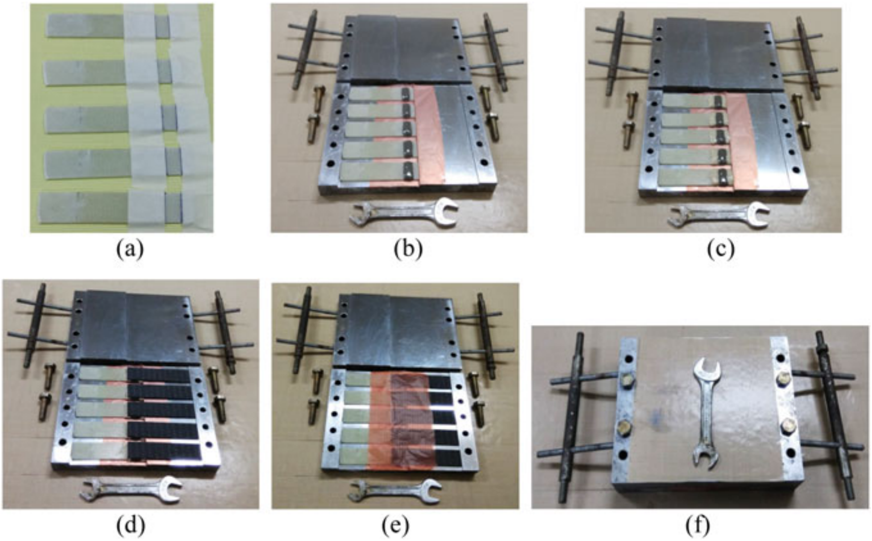


Fig. 8 Details about fabrication of dual adhesive bonded joint S4 specimen: **a** Ends of the overlaps are covered with mask tap, **b** GFRP adherends are placed in the mould with portion (40% of the bond length) of AV138 brittle adhesive at center of the bond, **c** Araldite-2015 ductile adhesive applied at the ends of the bonded regions, **d** Positioning of CFRP adherends, **e** Bonded regions are covered with releasing film and **f** Mould closed for adhesives curing

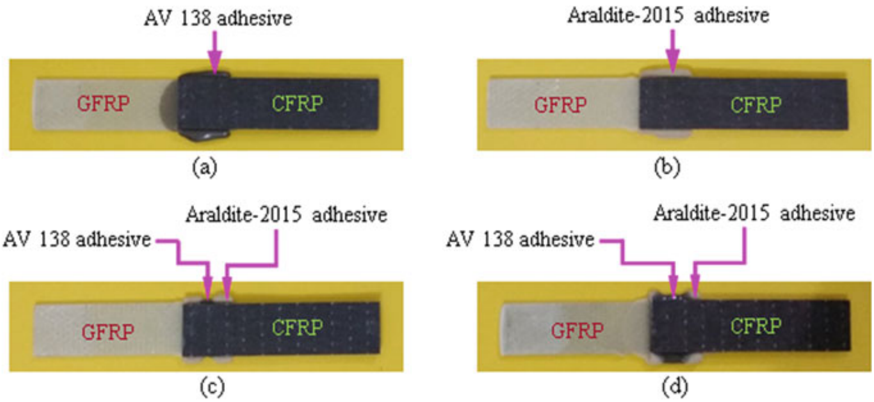


Fig. 9 Single and dual adhesive bonded joint specimens from the mould after curing: **a** S1 specimen, **b** S2 specimen, **c** S3 specimen and **d** S4 specimen

specimens by observing the colour difference of the adhesives. The extra squeezed-out adhesive portions are not required and those portions are removed by filing.

4 Experimental Testing

The X-ray radiography testing has been carried out to assess the quality and conditions of the bonded joints because the bonded region is hidden between the adherends. Then the specimens are prepared with end tabs at the grip region to minimize the eccentricity in loading. Tensile testing has been performed using MAKRON Universal Testing Machine (UTM) according to ASTM D 5868 standard.

5 Results and Discussions

X-ray radiography testing ensures that the prepared specimens are in good condition and no volumetric defects have been detected. These specimens are used for carryout tensile testing. The failure loads obtained by tensile testing for different single and dual adhesive bonded joint specimens are presented in Fig. 10.

From tensile testing, it is found that the bond strength or failure load for S3 specimen is more as compare to all other specimens due to the presence of small portion of brittle AV138 adhesive along with ductile Araldite-2015 adhesive and effectively resists the failure load. Hence, detaching of the adherends from adhesive is not easy at the interface. As the portion of the brittle adhesive AV138 increases at the center of the bond as in the case of S4 specimen and the corresponding bond strength reduces but still better than single adhesive bonded joints (S1 and S2 specimens). These kinds of observations are explained and discussed in detail and can be found from [10].

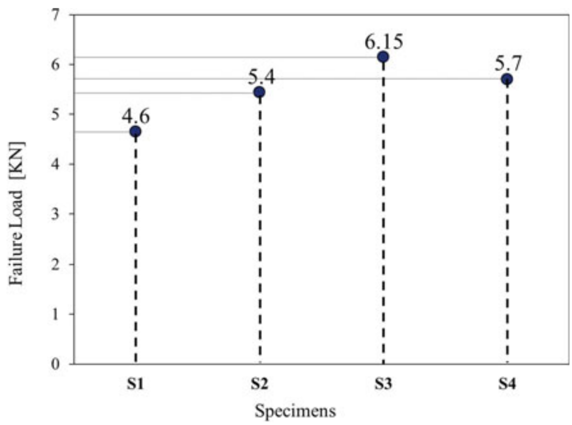


Fig. 10 Failure loads for different single and dual adhesive bonded joint specimens

6 Conclusions

The CFRP and GFRP laminates have been manufactured using hand layup and vacuum bagging method. Special designed mould is used to fabricate composite single and dual adhesive lap joints using AV138 brittle and Araldite-2015 ductile adhesives between CFRP and GFRP adherends. This designed mould helps to maintain uniform bond line thickness. Single and dual adhesive bonded joints are relatively easy to manufacture in a designed mould using different adhesives between dissimilar composite adherends (CFRP and GFRP) according to ASTM D 5868 standard.

The X-ray radiography testing has been carried out to assess the quality of the specimen. Tensile testing has been performed for obtaining the failure load for different specimens. From tensile testing, it is found that the single ductile adhesive Araldite-2015 bonded joint (S1 specimens) shows high bond strength compared to single brittle adhesive AV138 bonded joint (S2 specimens). For single adhesive bonded joints (S1 and S2 specimens), failure occurs at the interface. Whereas for dual adhesive bonded joints (S3 and S4 specimens) failure separation is not easy at the interfaces between the adhesive and adherends and thereby increases the bond strength. Hence, dual adhesives bonded joints may be recommended to use for better performance of the structures.

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Perceptions and Dynamics Affecting Acceptance of 3D-Printed Bridal *Lehenga* in India

Indranil Saha and Deepak John Mathew

Abstract In India, the wedding industry is booming as a result of growing affluence. Indian brides are inclined towards spending an extravagant amount on exclusive, high-fashion, designer bridal wear. There is, however, almost no published research that examines the aesthetic and other preferences of bridal couples in India in respect of bridal wear, including how predisposed couples are to innovate in its design. 3D printing is a popular aid in visualizing prospective designs and in prototype testing, being gradually applied in the creation of haute couture and mass-produced fashion products. The paper reports research on consumers' attitudes towards and use intention regarding 3D-printed bridal *lehengas*. Data was collected from Indian bridal wear consumers and decision-makers through semi-structured interviews. The results suggest that respondents had a positive attitude towards the technology, having a higher perception of the aesthetics and wearability of 3D-printed bridal *lehenga*.

Keywords Additive manufacturing · Bridal wear · Consumer adoption · Qualitative · Technology acceptance model (TAM)

1 Introduction

Additive manufacturing, conversationally known as three-dimensional (3D) printing, is an increasingly common aid in the visualization of designs and prototype testing, particularly in the fields of aircraft manufacturing, tissue engineering, and medical implants [1, 2]. Gradually, however, additive manufacturing is being applied to the design and production of customized fashion products such as, apparel, footwear, sunglasses, watches, and jewellery [3, 4]. The use of 3D-printing in respect of apparel consist of several steps, beginning with product design and extending across the

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A. Chakrabarti and M. Arora (eds.), *Industry 4.0 and Advanced Manufacturing*, Lecture Notes in Mechanical Engineering,
https://doi.org/10.1007/978-981-15-5689-0_18

digital creation of a 3D model, dividing the 3D model into a sequence of 2D slices, and then printing the sequence slice-by-slice into a 3D product [5]. From a design perspective, 3D printing allows to design apparel with more freedom by allowing them to explore former technical restrictions. This is particularly relevant for the apparel industry, which integrates the elements of design and creativity. Furthermore, 3D printing provides scope for mass customization to match market demand for variety in accessories and clothing [6], offering consumers the possibilities to receive products that match their individual preferences and requirements [7]. Hence, 3D-printed apparel is projected to be the future of fashion. In comparison to apparel, direct and indirect additive manufactured accessories have more material choices. In the past decade, some eminent fashion designers have introduced 3D printing into their practice. The Dutch, haute couture designer Iris Van Herpen has been a main innovator here with her use of 3D printing to radically extend garment construction materials and techniques. New York's studio Bitonti has used, Selective Laser Sintering (SLS) to create new, flexible net materials for use in apparel design. 3D-printing apparels has the potential to transform apparel design and production and through this consumers' experience of fashion [7].

Currently, however, its application to apparel is limited to a small section of the high-end fashion market, where fashion consumers are prepared to pay distinctive, innovative garments. This paper examines the scope for the use of additive manufacturing in the Indian market for luxury, premium, and budget bridal wear. The rise of the Indian fashion industry has impelled many Indian brides to move away from the tradition in dressing in their mother's or grandmother's bridal clothes and rather purchase high-end designer bridal wear, this new trend being promoted through social media, bridal magazines, and designer websites [8].

Apparel created through additive manufacturing has been introduced at major fashion weeks globally, but there is no evidence of its application to Indian bridal wear, there being minimal, in-depth academic research and publications on its use [9]. While the basic design and production procedures for the application of 3D printing in the context of fashion have been studied [10], there is no research that specifically examines consumers' attitudes to its use as a key consideration. The economic importance of the bridal wear category within India, fashion market is massive and growing at a fast pace [11, 12]. The trend is for contemporary Indian brides to spend an extravagant amount on high-fashion designer bridal wear, but there is no evidence of published research examining the attituds towards design innovation, with respect to bridal *Lehenga*s, a full, ankle length skirt elaborately embroidered and ornamented with beads, thread work, and mirrors and worn with a midriff blouse and a shawl, which is the traditional wedding dress of north Indian women. Hence, the aim of the study is to examine how several elements comprehensively impact and define consumers' perceptions, attitudes, and adoption intention regarding 3D-printed bridal *Lehengas.*

The research gap is addressed from the perspective of the technology acceptance model (TAM) [13], which is widely applied in researching consumers' perceptions, attitudes, and acceptance intention to technology [14]. Different sectors of consumers' perceptions, attitudes, or adoption of technology study have proposed varied external variables to further extend the TAM [15]. Understanding which elements play a major role in shaping consumers' perceptions, attitudes, and adoption intention could guide fashion designers and developers in targetting specific characteristics in the creation of 3D-printed bridal *Lehengas*. Consequently, the objective of the current study was to answer the following research questions:

Q1: How are consumers' perceptions, attitudes, and adoption intention concerning 3D-printed bridal *lehenga* influenced by external variables?

Q2: What are the major deciding factors that influence consumers' perceptions, attitudes, and adoption intention concerning 3D-printed bridal *lehenga*?

2 Literature Review

2.1 Additive Manufacturing

Additive manufacturing has gradually gained prominence in numerous areas of business and everyday life [16], the technology being an outcome of developments in a range of diverse technology areas. Additive manufacturing technology produces objects from 3D data, generally incorporating different materials, layer upon layer, into a product through the manufacturing process, marking a clear difference from conventional subtractive production systems [17]. Petrick and Simpson [18] describe additive manufacturing technology as disruptive in influencing profound change to processes in design, manufacturing, supply chain [19], logistics [20], product life cycle planning and control [21] and consumer behavior [22]. According to the Royal Academy of Engineering [23], additive manufacturing technology "*has the potential to replace many conventional manufacturing processes, but is also an enabling technology allowing new business models, new products and new supply chains to flourish*".

Mani, Lyons, and Gupta (2014) [24] suggest a number of benefits of additive manufacturing, including (i) material wastage when compared to mass production processes. (ii) elimination of the need for specific tools or equipment (iii) the capability of generating enhanced functionally through lightweight parts (e.g., reduced weight of particular components may cause reduced requirement of effort to travel around) (iv) decreased need for maintaining large amounts of raw materials within the supply chain, warehouse and transportation. (v) the capability of generating optimized geometries with near-perfect strength-to-weight ratios compared to wrought material, and (vii) less impact of the generated part over its life cycle, resulting in a reduced environmental impost and an improved economic model. These advantages suggest additive manufacturing should be explored in varied fashion and lifestyle categories to see how it can enhance the design and manufacturing process and product experience.

2.2 Wedding Industry and Bridal Wear in India

Wedding ceremonies are momentous, ritual occasions, seeing families invest significant resources in their staging [25]. Internationally, this has not always been the case. For example, before the twentieth century, Americans preferred modest weddings [26]. During the 1920s, however, the American wedding industry promoted the idea of luxurious wedding ceremonies as an expression of romantic love in a successful effort to elevate the consumption of products linked to romance, this including special bridal wear as an essential component of a wedding ceremony. The wedding day has been observed as a very important day of life, and the bridal wear has been treated as a sacred component [27]. Extravagant bridal wear is expensive, often being beyond the means of many couples, and has an environmental cost due to the amount of material involved and in being worn only once [25]. Its standardized luxury characteristics can also conflict with gender and religious diversity [27].

In 2017, Nikkei Asian Review reported the size of the Indian wedding industry to be $40 billion with an annual growth rate of 20–30%, with more than 10 million marriage ceremonies being held in India annually and the families tending to spend 20–30% of their lifetime income on the grandeur of the wedding. According to an article in The Conversation, bridal wear is one of the most important contributors to the sumptuousness of a wedding. In 2017, Indian brides spent between £4000 and £40,000 on designer bridal *lehenga* [28], suggesting the need for robust, consumer-oriented research on the taste preferences of Indian bridal couples.

2.3 Theoretical Framework

Perceived usefulness and perceived ease of use are the two primary determinants of consumers' technology adoption behavior under the technology acceptance model (TAM) [13] (Fig. 1). Perceived usefulness refers to the level of improvement in a consumer's task performance while perceived ease of use refers to the level of effortlessness in the use of a product due to the intervention of technology [13]. The field of the fashion research has adopted TAM as a valid theoretical framework

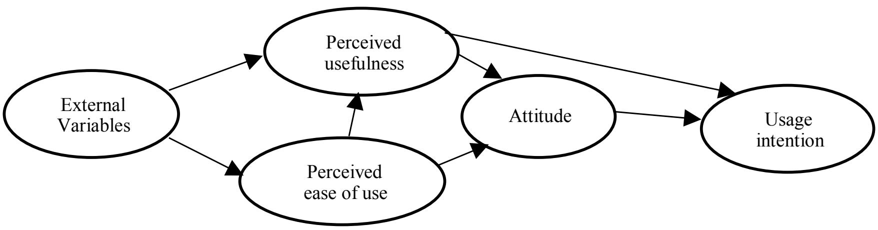

Fig. 1 The original technology acceptance model [13]

to examine technology application in areas such as, smart clothing [29], wearable technology [30] and solar-powered clothing [31].

Here, Perry [32] studied [5], three external variables to extend TAM within 3D-printed bridal apparel context. As 3D-printed bridal *Lehenga* is a technology-based apparel and its key evaluation criteria are assumed to be aesthetics [33] and functionality[32], the extended variables to TAM are general conviction about technology and tech optimism [34], consumers' perception of expected design, aesthetic elements [31] and expected performance [35], were chosen.

Technology optimism

Technology optimism is based on the idea that technological interventions offer people better control, flexibility, and efficiency in their lives [36]. Optimists are likely to think well about everything rather than giving importance to possible negative outcomes [37]. Previous studies suggest that positive emotions, such as amusement and optimism enhance consumers' aesthetic experience [38]. Additionally, optimism also influences products' perceived functional performance [39]. Previous studies connected to TAM have used technology optimism to examine ease of use, and perceived usefulness in various sectors [37, 15]. Some studies have also linked optimism with behavior intention. For instance, a qualitative study by Gilly, Celsi and Schau [40] concluded that technology optimism directly led to technology acceptance [41]; while a quantitative study by Liljander, Gillberg, Gummerus and Van Riel [42] indicated that optimism led to the continual consumption of new technology [43].

Aesthetic Features

Aesthetic features refer to product appearance and the level to which it is perceived as pleasing [44]. Literature suggests that aesthetics define the first impression of a product, while a product's look feasibly influences its perceptions of performance, strength, and weight which further influence perceived ease of use [40]. For instance, a thick leather jacket is expected to be sturdier than a thin linen shirt. Studies that connect aesthetics, usefulness, and ease of use, integrating TAM as theoretical framework are mostly quantitative and examine positive influences in mobile phones [45], online shopping [46], virtual clothing organizers [15], and healthcare systems [42]. Some studies also link product aesthetics to behaviors, such as purchase, re-visit, and recommendation intention [38, 40, 46]. This study examines how adoption behavior is influenced by aesthetics via performance, usefulness, ease of use, and attitude. These findings are used as a guide to designers and developers to optimise product aesthetics [40] with respect to 3D printed bridal *Lehenga.*

Expected Performance

Expected performance refers to the level at which a product performs as per expectation [35]. Although performance is a crucial element in comprehending consumer's attitude towards products' practicality in the adoption of technology [47], the original TAM does not give much importance to product performance [48]. Previous studies report that when a product's expected performance meets users' requirements, the product is perceived to be useful and easy to use [48]. However, when a product does not perform as expected, consumers develop a disapproving attitude [49]. Moreover, the expected performance is also directly connected to behaviors such as positive purchase intention [48].

This study explores the interrelationship of technology optimism, aesthetic features, and expected performance as external variables and how they influence perceived ease of use and usefulness, which can lead to product acceptance behavior and attitude.

3 Methodology

3.1 Sample

Yin [50] describes purposive sampling as a thoughtful manner of choosing the interview participants in qualitative research to include those who will yield the most relevant and plentiful data, given the topic of study. To meet the objectives of the study, a purposive sample was created from the customer database of total ninety eight luxury, premium, and budget bridal wear stores from a city in India. A sample size of between fifteen and thirty interviews seen as adequate to identify patterns across the data in qualitative interview research [51].

Within each category of store, up to twenty five participants were randomly selected from those who shared a valid contact number and a 'specified time' that fitted within the interview period (January 2019–February 2019). As family members are decision-makers in the particulars of Indian weddings [52], participants were a mix of brides-to-be and other family members. Informed verbal approval to participate in the interview was obtained from the members before the interview began. Out of the selected purposive sample of twenty five who were telephoned, fifteen volunteer respondents were successfully reached, including five family members and ten brides-to-be, after rejections and other exclusions. Interviews averaged twenty four minutes in length (range fifteen to forty two minutes).

3.2 Data Collection

Interviews followed a semi-structured guide to query participants' perceptions, attitudes and usage intention regarding 3D-printed bridal *Lehengas*. Prior to conducting the interview, a one-page information sheet and online video links were provided to participants to introduce them to 3D-printed haute couture and ready-to-wear fashions, including lingerie, wearable art, and accessories. Participants were asked open-ended questions based on the external variables identified by review of literature. For example, "what it is like" to have modern technology-based components when it comes to bridal apparel, what "sorts of elements are expected", as aesthetic and performance features, how technology, aesthetics, and performance of the 3D printed apparel links with the perceived ease of use and acceptance intention. Pretesting with five pilot sample was undertaken to refine the interview guide prior to use. Interviews were conducted in Hindi and English and transcribed for analysis. Demographic characteristics of each respondent, including age, gender, ethnicity, were partially provided by the stores. Other demographic details like education, marital status, employment status, household income, region of residence were collected during the interview process.

3.3 Data Analysis

A theoretical thematic analysis approach, which is guided by existing theory and theoretical concepts [53] and has been used to research a wide range of topics, e.g., women's clothing practices [54, 55], was used to analyze the data. The data was transcribed into written form first and then two researchers (IS and DJM) read the transcripts to recognize a primary list of items from the data set that have a reoccurring pattern. After that, extensive patterns in the data were focused on linking coded data with proposed themes. The initial themes were reworked and interrelations were explored and established in the next phase, and finally the report is documented on the refined themes that made meaningful insights with respect to the research questions.

3.4 Delimitation of the Study

This research is limited with the restrictions of purposive sampling. The study is also limited to bridal *Lehenga*, excluding other bridal apparel categories found in India.

4 Results

This section presents the findings of the semi-structured interviews by providing a complete summary of the data.

4.1 Sample

A purposive sample of 25 was selected and telephoned. After rejections and other exclusions, 15 volunteer respondents were successfully reached, including five family members and 10 brides-to-be. Interviews averaged 24 min in length (range 15–42 min).

Respondents' mean age was 30 years (range 23–51 years); 67% of participants were bride-to-be and between 23 and 26 years of age. All respondents were female. A significant proportion of respondents were employed (80%). 73% of the participants were *Punjabis*, 20% of them were *Marwaris* and 7% were *Gujaratis.* 30% of the participants, who were from the luxury consumer database had annual monthly income more than Rs. 30 lakhs. 53% of the respondents lived in the eastern part of India and 27% respondents' area of residence was northern part of India. Table 1 demonstrates the demographic details of the participants.

4.2 Major Themes

Participants referred to four major themes when discussing their perceptions, attitudes and acceptance regarding 3D printed bridal *Lehengas*: (i) Curiosity about the technology, (ii) Material comparison with existing textiles, (iii) Versatility and exclusivity of designs, (iv) Time and Cost involved.

Curiosity about the Technology

A common theme was inquisitiveness about 3D printing technology and its application to fashion. Most participants were familiar with 3D printing in other sectors, but a few respondents, mostly family members, were new to the concept of 3D printing. Some participants enquired about the process of 3D printing, expressing excitement about this new technology. A bride-to-be customer (25 years) contacted via the luxury store commented: "*I have seen many application of 3D printing technology. I recently saw a video on Facebook where an entire house was 3D printed… But I haven't really seen anyone wearing 3D printed dress in my circle…no…wait…one of my colleagues was wearing a funky pendant and she told me that it was gifted by her brother who got that 3D printed for her. I found it damn cool…. But never saw anyone wearing a garment around…Online videos of 3D printed garments look interesting though…How do they print the entire garment?*" Participants conveyed interest in the technology being merged with existing technologies. A bride-to-be customer from premium store wondered: "*Will the 3D printed Lehenga also have blinking lights with movements or will it change colors at times?*" While bride-to-be interviewees were more interested to know about the technological interactions, the family members were more concerned about the possible hazards of wearing such clothing on a wedding day.

Material Comparison with Existing Textiles

A common theme was concerns related to the material. The common material for 3D printing being plasticbased, participants made interviewees skeptical about the touch and feel of 3D printed *Lehengas*. Interviewees also suggested that instead of using 3D printing to make the entire *Lehenga* 3D, it could be made from a combination of

Table 1 Demographic profile of the respondents

Demographics	Total	Percentage
Age (mean; years)	30; (range 23–51 years)	
Customer type		
Luxury store	6	40.00
Premium store	5	33.00
Economy store	4	27.00
Gender		
Female	15	100
Ethnicity		
Punjabi	11	73.33
Marwari	3	20.00
Gujarati	1	6.67
Education		
School-level	3	20.00
Bachelors	9	60.00
Masters and/or higher	3	20.00
Marital status		
Married	5	33.33
Unmarried	10	66.67
Employment status		
Employed	12	80.00
Unemployed	3	20.00
Annual Household Income (INR)		
Less than 10 Lakhs	3	20.00
10–20 Lakhs	3	20.00
20–30 Lakhs	3	20.00
More than 30 Lakhs	6	40.00
Region of residence		
North India	4	26.67
East India	8	53.33
North-east India	1	6.67
South India	2	13.33

conventional fabric and 3D printed materials. A participant (24 years) commented, "*I am not too sure how plastic material will feel on the body…but if it can combine layers of net fabric or satin, which feel soft on the skin, maybe it will work*". Participants were concerned about the possible reaction of a wearer's body to the 3D printed material. A 49-year-old mother said, "*I hope the material doesn't cause any skin irritation… during wedding a considerable time is spent in front of the flame… The Lehenga shouldn't start melting and create an unwanted situation!*" Participants expressed apprehensions while moving when wearing such material. A 26-year-old participant wondered, "*The bride should move around/sit freely wearing such Lehenga. Are you sure they can do that wearing such things?*" Views were an overall skeptical about the main material, although participants also expressed their interest in trying out something different to existing *Lehengas.*

Versatility and Exclusivity of Designs

Mostly, participants were very enthusiastic about the newness of the concept and the scope to wear an exclusive, 3D printed designs on their wedding day. A 26-year-old respondent remarked, "*I think our generation is more open towards experimentation. I, myself, have picked a dark wine colored lehenga for my wedding day, which is very unconventional.*" A few participants mentioned that in their opinion, bridal costume should be different and elite. A 51-year-old mother said, "*I will definitely want to choose a never-seen-before bridal garment for my daughter. My daughter will probably love a 3D printed Lehenga as she is tech savvy and always wants to be one step ahead of her friends...*" However, some participants were also doubtful about the acceptance of the appearance of 3D printed bridal wear among their social groups. "*I don't know how my friends and relatives will react if they see me wearing such thing on my wedding day… I wouldn't take that risk for the biggest day of my life… Even celebrities won't wear them at their wedding*". Several participants seemed more hopeful about 3D printed accessories, rather than the entire bridal attire.

Time and Cost Involved

Participants were concerned about the possible time and cost associated with 3D printed bridal *Lehengas.* They were curious to know how fast the entire *Lehenga* could be printed and whether there will be options for later alteration. One 24-year-old participant said, "*My friend's exclusive designer lehenga took months to get manufactured. Since you're talking about 3D printed lehenga, the process should be faster and then one can probably have more time to build on other elements or accessories around it.*" A few participants showed interest in knowing about the cost involved with 3D printed bridal apparel. A 39-year-old customer asked, "*Will 3D printed lehenga be costlier than the Lehengas available in the market? Are they going to be readily available and displayed at the stores like we see at the regular stores?*" Budget store customers also expressed their unwillingness about risking a large amount of money on 3D printed apparel as it is not tried and tested before. A 35-year-old customer of a budget store commented, "*We would like to invest in something which is familiar to everyone… This (3D printed apparel) seems to be totally bizarre and I won't pay for it unless it is accepted by the society first*".

5 Discussion

This study reveals the opinions, attitudes and usage intention of 3D printed bridal wear in the Indian context. This section discusses the outcomes based on the two research questions.

5.1 *How Are Consumers' Perceptions, Attitude and Adoption Intention Concerning 3D-Printed Bridal* Lehenga *Influenced by External Variables?*

In the interviewees' responses, discussion of the external variables of aesthetic features, expected performance and technology optimism were interrelated. Participants who were more technologically inclined and inquisitive were also found to be excited about the prospect of securing an exclusive design through 3D printing. Respondents who were optimistic about the technology and its unique aesthetic appearance also suggested that thoughtful design could enhance the utility of the *Lehenga to* augment functional features, these results being consistent with previous literature and conclusions [38, 40].

Participants indicated that designs that are more aesthetically appealing are also more useful and that they have a more positive attitude towards attractive designs. This suggests that aesthetics may have a greater influence on adoption intention than expected performance and technology optimism. Consumers were enthusiastic to purchase 3D-printed bridal *lehenga* in affording them an aesthetic edge, although this readiness was limited to the participants recruited through luxury stores. Ease of use in performance was also related to aesthetics.

The research findings suggest that value-added 3D-printed bridal *lehenga* adds features of usefulness and ease of use. As with functional or smart clothing that can perform multiple actions or have various innovative features, if the proposed 3D-printed bridal *lehenga* has any special functions, the adoption intention is likely to be positively influenced. Even though 3D-printed bridal apparel can provide a better-fit, this improved aspect of performance was not substantial enough to influence the interviewees to adopt 3D-printed bridal *lehenga* unless they promised ease of use. In other words, usefulness and positive attitude were more related to adoption intention than performance.

5.2 *What Are the Major Deciding Factors in Consumers' Perceptions, Attitude and Adoption Intention Concerning 3D-Printed Bridal* Lehenga*?*

Perceived Ease of Use

Perceived ease of use was largely influenced by both technology optimism and performance. The interview results indicate that performance is more important than a positive attitude towards technology when reflected from an ease of use viewpoint.

Perceived Usefulness

Perceived usefulness was largely affected by both aesthetics and performance. The results indicate that usefulness is appreciated functionally as well as aesthetically. Nevertheless, functionality is considered more important than aesthetics when it comes to the perception of usefulness.

Attitude toward Use

The interviewee's attitude towards purchasing 3D-printed bridal *lehenga* was largely influenced by all three external variables (technology optimism, aesthetics, and performance) as well as mediating factors (ease of use, and usefulness). The results indicate that consumers' attitudes toward 3D-printed bridal wear were mostly determined by exclusivity of look and performance. Technology optimism, usefulness, and ease of use were identified to have lesser important roles.

Adoption Intention

Adoption intention was affected by aesthetics, usefulness, and attitude toward use. The results indicate that attitude towards use has the stronger influence on adoption intention.

6 Conclusion

Taking the lead from TAM [13], the current study used three external variables to examine how these dynamics had an impact in defining consumers' perceptions, attitude toward use and adoption intention in respect of 3D-printed bridal *lehenga.* The outcomes largely explained the research questions and supported the extended TAM.

The results suggest that all external variables were interrelated in the interviewee's thinking. Participants who were more optimistic about technology also had a higher perception of aesthetics of 3D-printed bridal *lehenga.* These participants also assumed that aesthetically pleasant design would provide better performance. Aesthetic features were more important than an optimistic viewpoint on technology in determining adoption intention. The current study also simultaneously examined the impact among the TAM variables to show that luxury consumers are more inclined and open towards trying out 3D printed bridal wear than budget store consumers.

Drawing on the directions of the present study, further studies may focus on building virtual prototypes of 3D printable *lehenga* in order to get direct feedback on consumer attitudes and preferences. More comprehensive inputs could also be gained from an increased sample size.

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Surface Morphology and Metallurgical Studies on Gas-Assisted Laser Beam Hybrid Micromachined Steel

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Abstract Micromachining with laser is an established technique used in different industries such as aerospace, automobile, electronic and medical industry. Compared with other processes of drilling holes, laser drilling has the ability to drill very precise micro holes with no tool wear. In the present work, an attempt is made to micromachine straight micro holes using the gas-assisted laser machine on 2 mm thickness steel workpieces. Effect of the input parameters such as laser power and assist gas pressure are studied on the output responses viz. entrance hole diameter, exit hole diameter and taper length. Laser-machined hole surface morphology is analyzed with the help of an optical microscope and scanning electron microscope. Surface metallurgical characterization is carried out to differentiate the recast layer, heat-affected zone (HAZ) and conversion layer by the material elemental composition.

Keywords Laser micro-drilling · Gas pressure · Laser power · Hole diameter · Hole taper length

1 Introduction

There are extensive studies for laser drilling in various applications such as aerospace industries, automobile industries, electronic industries, etc. [1]. The conventional drilling, techniques employed often lead to a rough surface, more machining time, non-repeatability, tool wear, low machining rate and inaccurate hole diameter. Laser

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A. Chakrabarti and M. Arora (eds.), *Industry 4.0 and Advanced Manufacturing*, Lecture Notes in Mechanical Engineering,
https://doi.org/10.1007/978-981-15-5689-0_19

drilling is an inexpensive and flexible alternative to replace conventional hole drilling methods. Almost all the materials such as mild steel, alumina, glass, copper, and composites can be drilled by laser drilling with high accuracy, repeatability and reproducibility [2]. Laser machining is mainly a non-contact type technique eliminating tool wear and also reduces the limitations to shape formation with minimal sub-surface damage. Comparing other commercially available lasers, CO_2 laser has several advantages such as low operating cost, few processing steps, high cutting quality, narrow incision width (general 0.1–0.5 mm), high precision and highly-flexible CNC programming of shapes for engineering prototyping. The CO_2 lasers are available with a wide range of average power, output ranging from a few watts up to over tenth of kilowatts, which helps for processing a wide range of materials. Therefore, CO_2 lasers are used for performing micromachining operations. In today's technological growing world laser micromachining (LμM) is an ideal choice for research and development, prototyping and batch production of novel ideas. Micro-holes are one of the common microfeatures machined by CO_2 lasers [3]. Some of the applications include flat panel displays, hard-disk drives, printers, cameras, cellular phones, photocopiers, PC's, fuel injector nozzles, turbine blades holes and stents. There are many parameters such as laser power, frequency, gas pressure, number of scanning passes, scanning speed, focal point position which affect the hole quality. Proper control of these parameters is required to achieve the desired hole quality.

CO_2 lasers are commonly used for cutting, welding and drilling purposes. Several researchers carried out the experimental study to observe the effect of laser input parameters on cutting quality. Researchers carried out the cutting of aluminum [4], stainless steel [5, 6], high strength steels [7] and inconel [8]. Cutting quality is generally reported in terms of kerf width, edge roughness and the size of the heat-affected zone (HAZ). Wang et al. [9] studied the characteristics of laser welding. Authors welded advanced high strength steels and studied the effect of input process parameters on microstructure and mechanical properties. Hengfu [10] machined the microchannels on polymethylmethacrylate by CO_2 laser. A relationship between laser power, scan velocity, number of passes and microchannel depth was acquired. The influence of CO_2 laser input parameters during micro-drilling of different carbon content steel is studied by Chen et al. [11]. With an objective to obtain a high-quality hole on ceramics with low taper and low spatter deposition, Yan et al. [12] carried out the experimental and numerical study. Some authors also reported the effect of the pulse duration of CO_2 lasers on the drilled hole quality [13, 14]. Thermoplastic polymer was drilled by Masmiati and Philip [15]. Best combination of laser input parameters for improved hole quality in terms of taper and circularity of hole was reported in the study. Hirogaki et al. [16] did an experimental study of drilling blind holes by CO_2 lasers on the printed wiring boards. Nagesh et al. [17] reported the effect of adding carbon nanopowder during the laser drilling. Carbon black dispersed vinylester/glass is drilled by laser. Authors reported that the taper angle is reduced by the addition of carbon black and performing experiments at high laser power. In the recent developments, researchers carried out underwater machining by CO_2 laser. Authors reported that underwater laser machining produces surfaces with reduced substrate defects [18]. Tsai and Li [19] also carried out a similar study on underwater laser machining of LCD glass and alumina. Authors reported that the distance between the two drilled holes underwater is less than that drilled in air. This is due to the reduced microcracking and affected area by heat of the laser underwater.

As found from the literature survey a considerable number of the researchers concentrated their work on CO_2 laser cutting. Few studies were carried out on laser drilling of thermoplastics, glass, ceramics and metals. Still, detailed study is to be done to study the influence of CO_2 laser on the drilled hole quality, recast layer, heat-affected zone, conversion layer and dross. So, in the present investigation, CO_2 laser is used for drilling micro holes in AISI 1040 steel workpieces. Experiments are performed to study the effect of process parameters on hole quality. Scanning electron microscope (SEM) and energy-dispersive X-ray spectroscopy (EDX) analysis are conducted to study morphology and elemental composition of the hole surface. From EDX analysis the elemental composition of the recast layer, HAZ and conversion layer are studied.

2 Experimentation

In the following section, the experimental setup, material, input conditions, experimental procedure of laser drilling are described. Various laser input process parameters and their ranges are given in Table 1.

2.1 CO_2 Laser Test Set up

The experiments are conducted on AISI 1040 steel using air-assisted CO_2 laser machine of 2500 W power. The experimental setup showing the laser head and the workpiece is shown in Fig. 1. Oxygen is used as an assist gas in the present work.

2.2 Experimentation

Experiments are conducted to study the effect of input process parameters and to obtain their optimum range for machining of a good quality hole. Experiments are

Table 1 Process parameters and their respective ranges

Input parameter	Range
Gas pressure (MPa)	0.5–0.9
Laser power (W)	1000–1500
Standoff distance (SOD) (mm)	1.000

Fig. 1 Overview of air-assisted CO_2 laser micromachining experimental setup

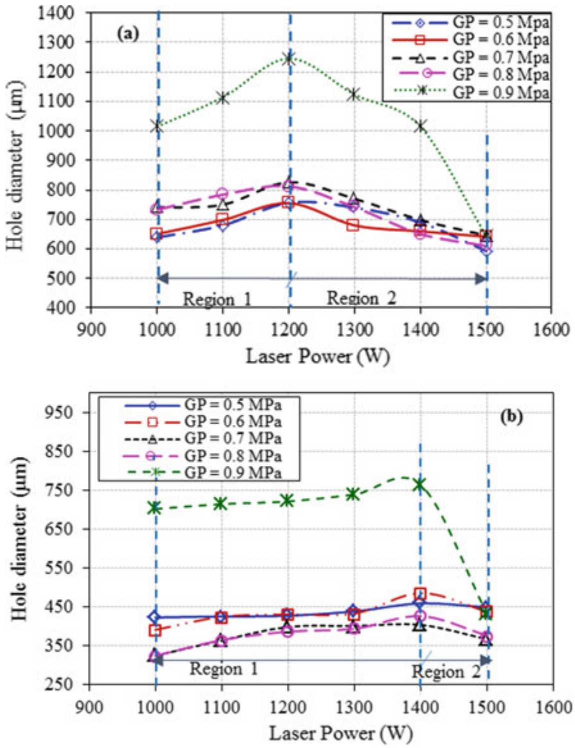
conducted by varying the input power, gas pressure and using O_2 as assist gases. Hole formation starts from 0.4 MPa but comparable good quality holes are starting from 0.5 MPa. So, 0.5 MPa is chosen as starting gas pressure in present experimental work. Experiments are planned and conducted for five levels. Maximum gas pressure is 0.9 MPa. A full factorial way is adopted for the design of experiments. The experiments are carried out with different combinations of process parameters. The standoff distance (=1 mm) is kept constant so as to keep the focal point minimum. The hole diameter is characterized by SEM and optical microscope.

3 Results and Discussion

3.1 *Effect of Laser Power and Gas Pressure on Hole Diameter*

The effect of laser drilling parameters laser power and gas pressures on hole entrance and exit diameter are shown in Fig. 2a, b respectively. The entrance hole diameters produced are in the range of 590–1250 μm for gas pressures 0.5–0.9 MPa and powers

Fig. 2 Effect of laser power on hole diameter for AISI 1040. **a** entrance diameter, **b** exit diameter



1000–1500 W. While, exit diameter of the hole varies from 320 to 765 μm. It can be seen that the entrance and exit hole diameter increases to a threshold value of laser power. The increase in the laser power increases the heat energy given to the material per unit time. This causes the increase in hole diameter throughout the thickness which can be seen in region 1.

Increase in diameter is observed up to the critical point of power, i.e. 1200 and 1400 W for entrance and exit diameters, respectively. Beyond the critical power 1200 and 1400 W the molten material in the melt front re-solidifies around the hole causing shrinkage in the molten material. Due to this phenomenon, the hole diameter stops increasing after the critical laser power which can be seen from region 2.

When very high powers are used spatter deposition takes place due to high melt ejection velocity and insufficient gas pressure. Figure 3 shows SEM images of the laser-drilled holes in AISI 1040 steel plates. These holes are drilled at laser power of 1500 W.

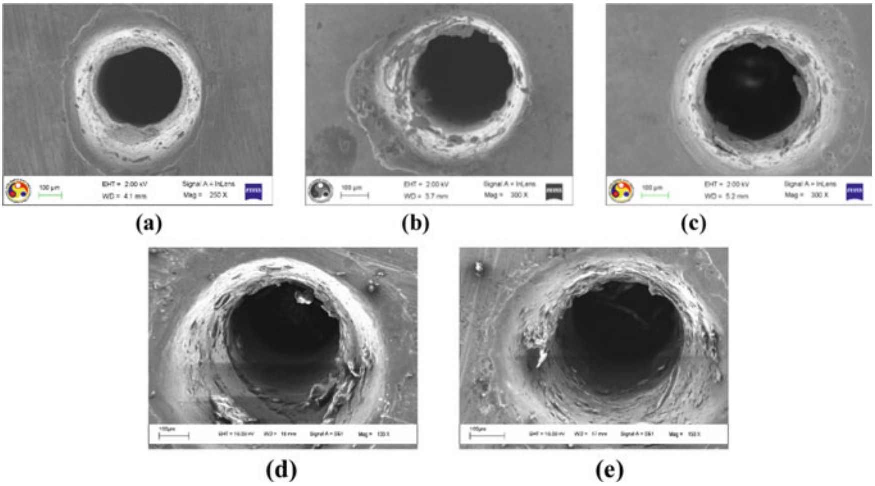


Fig. 3 Surface morphology of the laser micromachined holes at gas pressure. **a** 0.5 MPa, **b** 0.6 MPa, **c** 0.7 MPa, **d** 0.8 MPa and **e** 0.9 MPa

3.2 Effect of Laser Power and Gas Pressure on Hole Taper Length

Hole taper exists when the entrance diameter of hole is larger/smaller than exit diameter. The geometrical quality of the laser drilling can be represented by hole taper length, which is defined as

$$\text{Taper length} = (D - d)/(2) \tag{1}$$

where D is the entrance diameter and d is the exit diameter of the hole.

The relationship between hole taper length and laser power at different gas pressures can be seen from Fig. 4. The taper length decreases with the increase in power. At low powers, the laser intensity is insufficient to penetrate fully into the workpiece. Hence the entrance diameter is more and exit diameter is less when performed with low powers. When the laser powers are high the laser beam has a sufficient amount of energy to penetrate, thus forming a through-hole with less taper. For drilling higher is the laser power, lower the taper length.

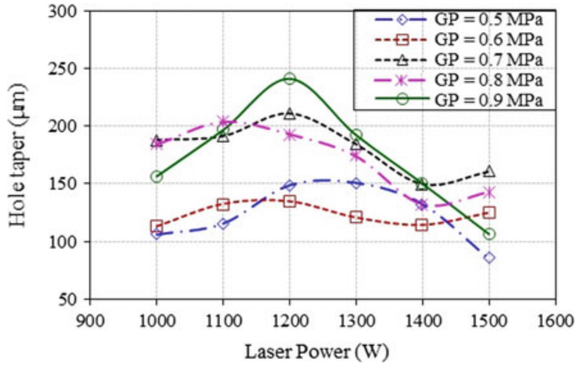


Fig. 4 Effect of laser power on micro hole taper length for AISI 1040

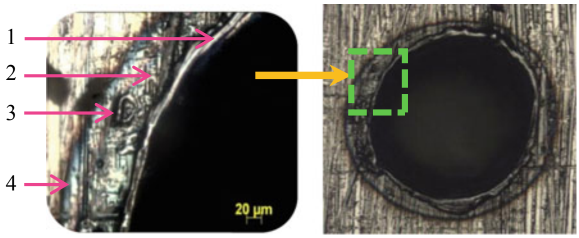


Fig. 5 Optical microscopic image of micromachined hole on AISI 1040 showing hole showing (1) recast layer, (2) heat-affected zone, (3) dross, (4) conversion layer

3.3 Surface Morphology and Elemental Composition Analysis

The surface morphology and the elemental compositional analysis are studied with the help of SEM. Morphology study is carried out of hole top surface which consists of heat-affected zone (HAZ), recast layer, conversion layer and dross (Fig. 5).

Dross is a solid impurity attached to the surface. It is the impurity that remained after solidification of the molten material. Figure 5 shows the image of the hole drilled with power 1500 W and gas pressure 0.7 MPa.

3.4 Elemental Composition of the Surface

The elemental composition of the surface is done with the help of SEM and EDX. It is used to differentiate the recast layer, heat-affected zone (HAZ), conversion layer and dross material by finding the elements in the desired location. In the present work, the EDX analysis is done for a hole drilled with laser power 1300 W and gas pressure 0.6 MPa.

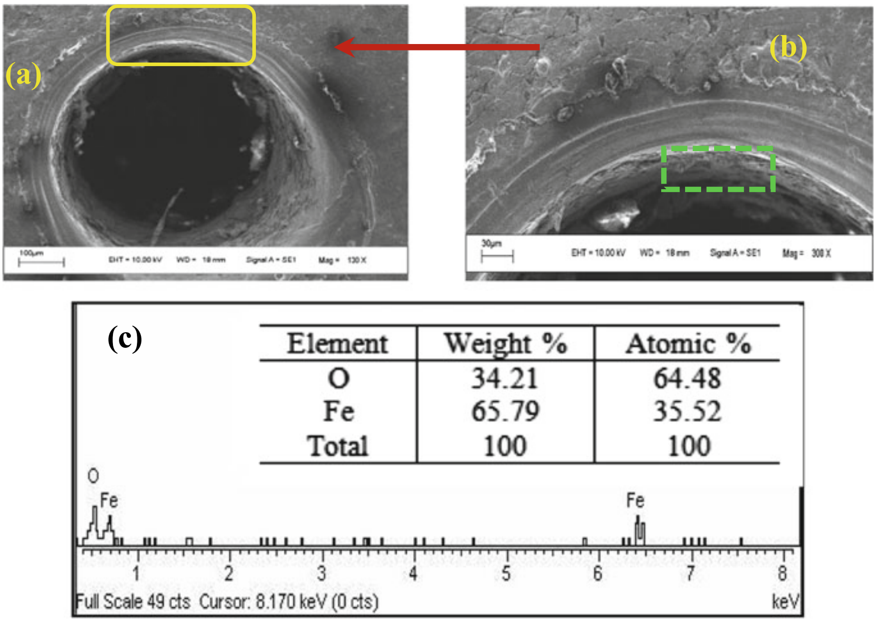
Elemental analysis for recast layer

The recast layer is the re-solidified layer of the molten material which is attached to the surface of the hole. It majorly consists of O_2 and Fe. As the assist gas used is O_2. The SEM image and the location where the EDX is done can be seen from Fig. 6.

From Fig. 6c, it can be seen from the atomic % that the O is twice that of Fe signifying the composition as FeO_2.

Elemental analysis for heat-affected zone

Heat-affected zone is the layer adjacent to the recast layer. It partially melts due to the melt front produced by the laser beam and grain structure is altered in this region. Figure 7 shows the SEM image of the HAZ. From Fig. 7c, it can be seen from the atomic % that the O is approximately equal to Fe signifying the composition as FeO.



Element	Weight %	Atomic %
O	34.21	64.48
Fe	65.79	35.52
Total	100	100

Fig. 6 **a** Surface morphology of the laser micromachined hole, **b** image showing recast layer and location where the EDX is done and **c** elemental composition showing ranges of Fe and O

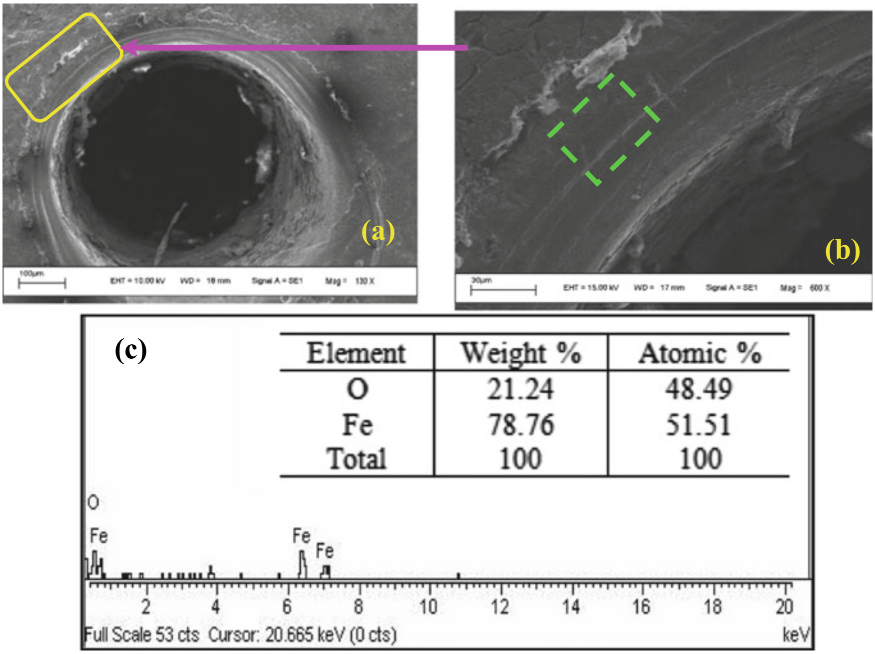


Fig. 7 **a** Surface morphology of the laser-drilled hole on AISI 1040, **b** image showing HAZ and location where the EDX is done and **c** surface metallurgy showing the ranges of Fe and O

Elemental analysis of conversion layer
This is formed due to heat from the melt front. Figure 8 shows the conversion layer where EDX is performed. From the elemental analysis, it can be seen from atomic % (approx.) that the conversion layer consists of Fe and a very small amount of oxygen.

Elemental analysis of dross
Dross is a solid particle attached to the molten material. Figure 9 shows the elemental analysis of dross. From the elemental analysis, it can be seen from atomic % (approx.) that the dross consists of three parts of oxygen and one part of Fe approximately. Thus, it signifies that it contains FeO_3.

4 Conclusion

In this paper, CO_2 laser drilling of AISI 1040 steel plates is successfully demonstrated and studied.

1 The minimum entrance diameter of hole produced in this work is 593.1 μm at 0.5 MPa gas pressure and 1500 W laser power.

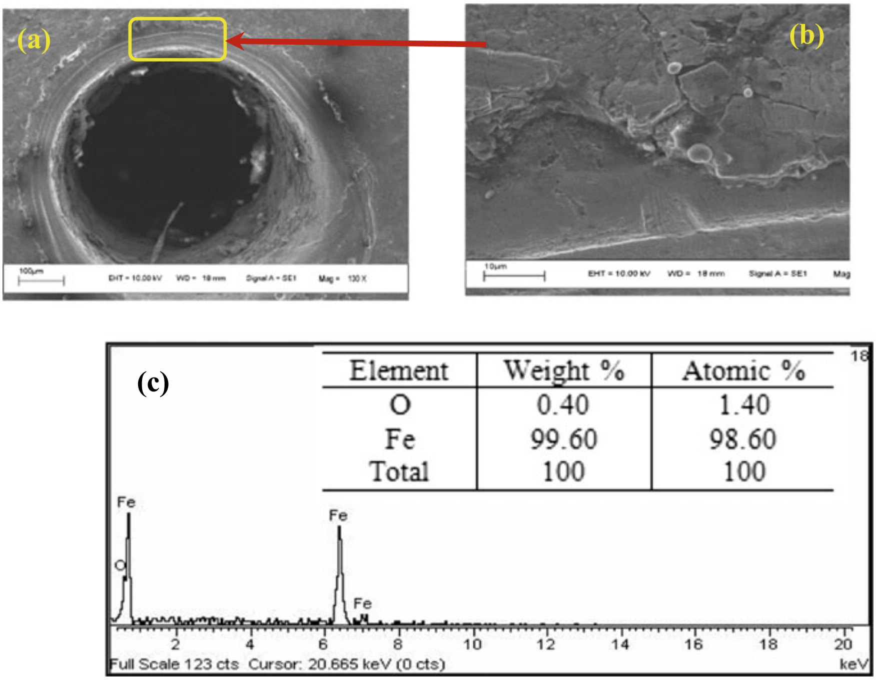
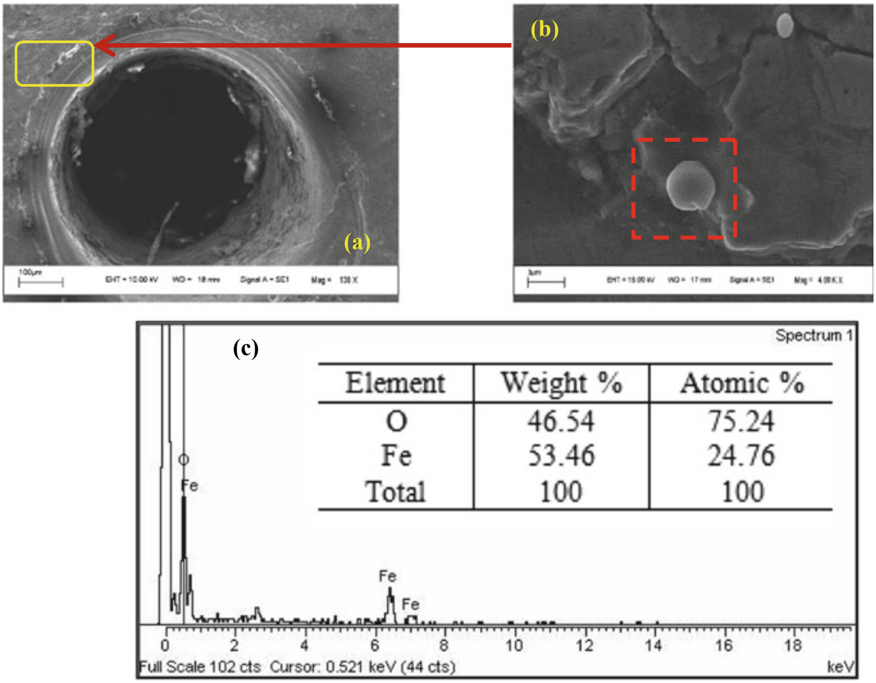


Fig. 8 **a** Surface morphology of the laser-drilled hole, **b** image showing C.L and location where the EDX is done and **c** surface metallurgy showing the ranges of Fe and O

2 It is also observed that the taper length decrease with an increase in power. The hole with a minimum taper length of 85.06 μm is obtained at 0.5 MPa gas pressure and 1500 W laser power.
3 Different zones of the machined surface, i.e. layers recast layer, HAZ and conversion layer are differentiated with the help of elemental analysis.
4 The obtained elemental compositions are FeO_2 in the recast layer, FeO in HAZ and Fe in conversion layer. The dross is also studied and the composition of the dross obtained is FeO_3.



Element	Weight %	Atomic %
O	46.54	75.24
Fe	53.46	24.76
Total	100	100

Fig. 9 **a** Surface morphology of the laser-drilled hole, **b** location showing where the EDX is done and **c** surface metallurgy showing the ranges of Fe and O

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A Study on the Tribological Behavior of Al/B_4C/Graphite Hybrid Composite Fabricated by Friction Stir Processing

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Abstract Aluminum and its alloys are used for aerospace and automobile applications because of their high specific strength. However, they exhibit poor wear resistance which limits their usage in many applications. To overcome this, in this work, aluminum has been reinforced with boron carbide (B_4C) and graphite using friction stir processing, thus, producing a hybrid aluminum matrix composite. This composite exhibited two times increase in the hardness (61 HV) as compared to the unreinforced matrix. The tribological performance of this composite was evaluated using a reciprocating sliding tester at different loads ranging from 1.96 to 5.88 N. To understand the wear characteristics, ex-situ analysis was performed on the worn surface of the processed composite using scanning electron microscope (SEM) and optical profilometer. The synergistic effect of B_4C ceramic and graphite reinforcements provided excellent tribological properties in both the abrasive and adhesive wear regimes with a 49% improvement in wear resistance, especially at higher loads.

Keywords Tribology · Friction stir processing · Hybrid Al-B_4C-Graphite composites

1 Introduction

Aluminum metal matrix composites (AMCs) are used in automotive and aerospace industries due to their good specific strength and superior wear resistance [1, 2]. Hard phases like SiC, Al_2O_3, etc., are generally reinforced into the aluminum matrix to enhance the tribological properties [3]. Composites with the solid lubricants embedded in their matrix can considerably reduce the friction and wear during sliding and also can be employed when liquid lubricants are impractical. It also curtails the need for external oil lubrication, modifies friction, and thus reduces the energy consumption maintaining the engineering sustainability [4, 5]. Friction stir processing (FSP) is an effective solid-state method for producing surface and

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A. Chakrabarti and M. Arora (eds.), *Industry 4.0 and Advanced Manufacturing*, Lecture Notes in Mechanical Engineering,
https://doi.org/10.1007/978-981-15-5689-0_20

bulk composites. In this method, a non-consumable rotating tool is plunged into a work piece and moved forward, resulting in severe plastic deformation and localized surface modification [6]. It also helps in dynamic mixing of the material underneath and therefore, surface composites can be produced without any agglomeration [7, 8]. As FSP is a solid-state process, multiple reinforcement particles can be evenly distributed together in the matrix even if there are any density differences [9, 10].

Therefore, it is hypothesized that producing hybrid composite with a ceramic and solid lubricant can provide enhanced tribological performance in wider regimes of wear and can also reduce the use of environmentally hazardous external lubricants maintaining the engineering sustainability. In this work, boron carbide (B_4C) and graphite were chosen as the reinforcements such that the former reduces the wear of composite in the abrasive regime and the latter in the adhesive regime. The composite is expected to exhibit better tribological properties making it suitable for a wider range of applications.

2 Materials and Methods

Commercially pure (CP) aluminum (Al-1100) was machined to plates of 6 mm thick, 80 mm wide, and 200 mm in length. These were utilized as matrix material for the processing, on which, grooves of 4 mm depth, 3 mm width, and 140 mm length were made using a milling machine. The grooves were uniformly filled with the mixture of boron carbide and graphite in 1:1 proportion by weight. The grooves were then sealed using Al strips with the help of hydraulic press. Custom built Five-axis Friction Stir Welding Machine (FSWM, Make: BiSS ITW) was used to carry out the processing with a tool rotation speed of 1200 rpm, traverse speed of 25 mm/min, and tool tilt angle of 2°. After each pass, the workpiece was allowed to cool to room temperature and six passes were done to ensure uniform distribution of particles. From the developed composite, flats of 13 mm × 13 mm × 5 mm dimensions were cut using wire electric discharge machining. In order to obtain uniform surface roughness on the flat, surface finishing was done to a roughness of ~Ra 554 nm by following the standard metallographic polishing methods. Before the tests, the surface was cleaned with acetone and dried to avoid any contamination. Hardness of the composite was measured using a micro Vickers hardness tester.

A reciprocating tribo tester (TR 282-M111 Ducom) with piezoelectric force sensor (PCB, Model 208C01, resolution 0.45 mN) and having a stroke length of 1 mm was used for evaluating the wear resistance of the composite. Steel balls of 6 mm diameter with a hardness of ~60 HRc were used as countersurface. The experiments were run for 2000 cycles (5 Hz ± 0.1 Hz) in ambient conditions. Experiments were also carried out on CP Al flats of similar dimensions for comparison purpose. Graphs were plotted for the coefficient of friction (COF) values obtained from the tribometer with respect to various loads. After the test, the worn surfaces of the composite flat were analyzed using an optical profilometer (Wyko NT1100) for obtaining the swept wear volume and scanning electron microscopy (Tescan Vega 3) studies were done to analyze the operating wear mechanisms.

3 Results and Discussion

Figure 1a shows the schematic of the process of composite fabrication using FSWM. Figure 1b, c shows the optical micrograph and SEM image of the processed composite and it is evident that the nugget zone is free from defects and particle agglomeration. Microhardness studies revealed that the composite exhibited two times increase in hardness reaching a value of 61 HV as compared to 27 HV of the unreinforced base material. In the produced composite, grain boundaries and reinforcement particles can act as dislocation barriers contributing to the increase in hardness (based on Orowan mechanism and Hall-Petch relationship) [10].

The COF and wear volume obtained for different loading conditions: 1.96, 2.94, 4.9, 3.92, and 5.88 N are plotted in Fig. 2a, b, respectively, which gives the comparison

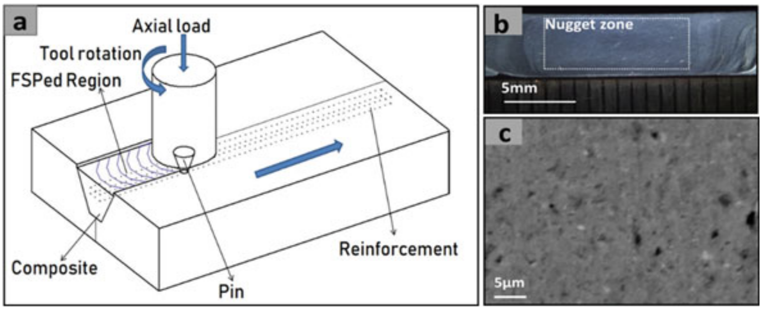

Fig. 1 **a** Schematic representation of composite fabrication by FSP, **b**–**c** processed composite

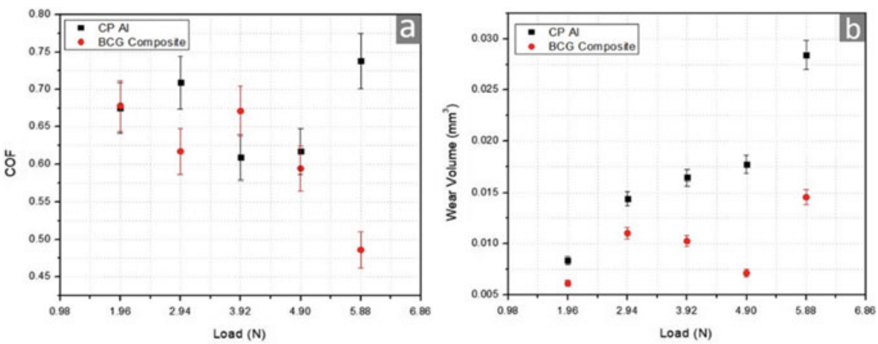

Fig. 2 **a** Variation in coefficient of friction (COF) with load, **b** variation of wear volume with load

between the tribological response of CP Al and Al-B_4C-Graphite hybrid composite (BCG composite).

In Fig. 2a, it can be observed that with an increase in the applied normal load, there was a slight increase in the COF for CP Al and decrease in that of BCG composite material, thereafter no significant change was observed until 5.88 N load. At this load, a high COF value of ~0.73 was observed for CP Al. However, at this load, the composite material showed a lower COF value of ~0.48, which is the least value compared to the all other loads for both the materials. The reduction in friction can be attributed to the lubricating effect of graphite in ambient conditions which reduces the metal-to-metal interaction. Similar observations were reported by other researchers when solid lubricants were used as reinforcements [4, 9].

Figure 2b shows the variation in swept wear volume for CP Al and BCG composite. From the figure, it can be observed that the wear volume for CP Al increases when the load is varied from 1.96 to 4.90 N. At load 5.88 N, it can be observed that there was a sudden increase in the wear volume. It was also observed that for the composite material, the swept wear volume was less than that of CP Al for all the loads. At 5.88 N load, there was a notable reduction in wear volume of the composite as compared to CP Al. Thus, the BCG composite exhibited an enhanced wear resistance of 49% compared to that CP Al at this load.

To study the wear characteristics, analysis of the worn surfaces of CP Al and BCG composite material for different loading conditions was done using optical profilometer and scanning electron microscope (SEM). Surface profiles and SEM images of wear scar corresponding to 2.94 and 4.9 N exhibited similar topographies to that of 1.96 N and 5.88 N, respectively. Hence, 3D surface profiles and SEM images of remaining three loads are reported. Figures 3a–c and 4a–c show the worn surface optical profiler images of CP Al and BCG composite material for different loading conditions. The profilometry image is attached with the color chart indicating the maximum wear depth. The high wear region is represented in the blue color. It can be observed that the surface damage increases with load, however, it was found to be lower for the composite when compared to CP Al. Wear volume values plotted in Fig. 2b were also obtained from the profilometry studies.

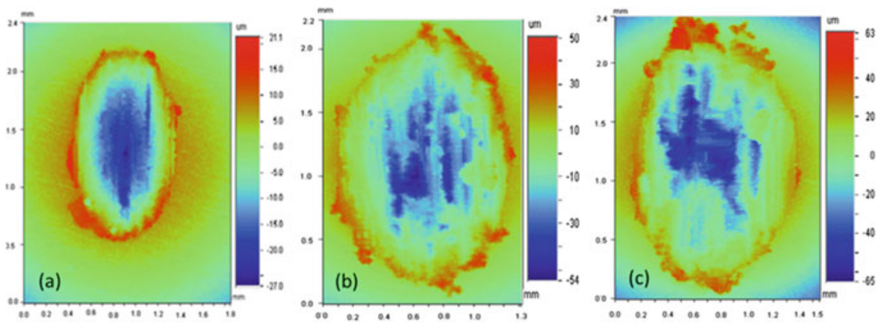

Fig. 3 **a**–**c** Optical profiler images showing wear characteristics of cp Al

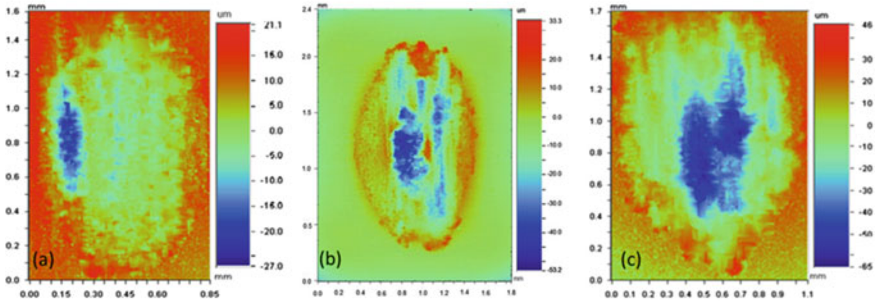

Fig. 4 **a**–**c** Optical profiler images showing wear characteristics of BCG composite

The maximum wear depth was generally observed at the center of the worn surface, and the corresponding values of wear depth for both the material with respect to their loading conditions are shown in Table 1. It can be observed that the wear depth of the composite was found to be lower than that of the CP Al at all loading conditions.

Figures 5a–c and 6a–c show the SEM images of the wear surface captured at 500 µm scale for CP Al and BCG composite for 1.96 N (a), 3.92 N (b), and 5.88 N (c) loading conditions, respectively.

In Fig. 5a, abrasive wear could be observed with minimal oxidation. Plowing marks are visible in the SEM image of worn surface. As reported earlier, the wear depth observed at this particular load was ~25.39 µm and can be due to the shallow grooves produced because of the abrasion at low loads. Fig. 5b shows the worn

Table 1 Maximum wear depth for CP Al and composite

Load (N)	CP Al (wear depth in µm)	BCG composite (wear depth in µm)
1.96	~25.39	~22.27
3.92	~53.98	~48.57
5.88	~62.06	~58.96

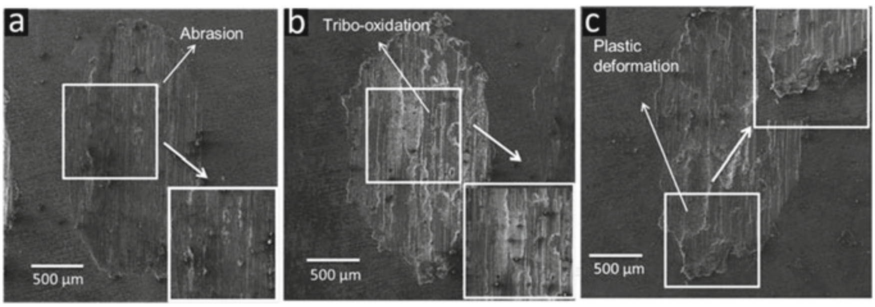

Fig. 5 **a**–**c** SEM image showing worn surface of CP Al

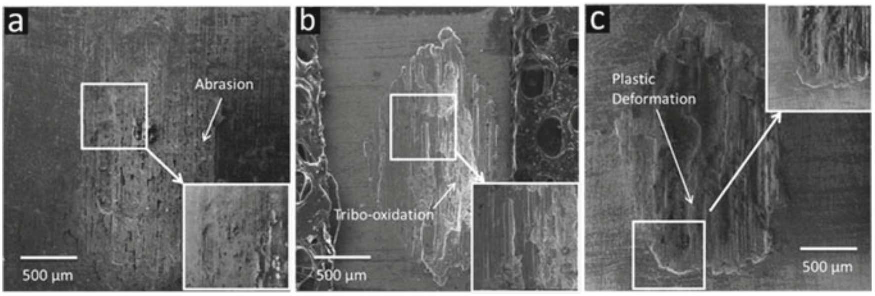

Fig. 6 SEM image showing worn surface of BCG composite

surface region of CP Al when the applied load was 3.92 N. A mixed mode of wear, both abrasion and oxidation, was observed in the wear scar. From Fig. 5c, it can be observed that adhesive wear was existing (shown in the detailed view) for load 5.88 N due to which there was a high COF value as shown in Fig. 2a. The plastic flow of material due to adhesion can be observed at the peripheral regions.

Figure 6a shows the worn surface SEM image of BCG composite tested at 1.96 N load. Abrasive wear can be observed from the image and the lowest wear volume was also observed for this load. BCG composite also exhibited the same surface wear characteristic as that of CP Al at this load, however, as reported in Table 1, the wear depth was found to be ~22.27 µm which was lower than that of CP Al. This indicates that the grooves produced due to abrasion is shallower than that of CP Al and can be attributed to the presence of hard B_4C ceramic which can resist wear especially in the abrasive regime. Similar to that of CP Al, mixed mode of wear was observed at 3.92 N, however, the wear depth being lower than that of CP Al at the same load indicates that the extent of damage and wear is lesser. At 5.88 N, adhesive wear was observed with plastic deformation at the peripheral regions. However, the COF values obtained for BCG composite at this load were 0.48 (Fig. 2a), which was lower than that of CP Al (COF value: ~0.73). This can be attributed to the influence of graphite acting as solid lubricant reducing the frictional values in the adhesive regime, thus, reducing the overall surface damage and wear.

4 Conclusion

A hybrid metal matrix composite with hard boron carbide (B_4C) ceramic particles and graphite (solid lubricant) as reinforcements was synthesized using friction stir processing. Reciprocating sliding tests were done to evaluate the tribological response of the produced composite. The following inferences can be made from the experiments conducted:

1. Compared to as-received CP aluminum, the composite showed a 49% improvement in the wear resistance at 5.88 N load which can be attributed to the synergistic effect of B_4C and graphite reinforcements.
2. From the SEM images and profilometry studies, the extent of wear at lower loads was found to be less for the composite. Hence, it can be understood that B_4C has enhanced the wear resistance of the composite in the abrasive regime.
3. From the obtained frictional values, it can be inferred that graphite has considerably reduced the frictional values at higher loads, thus providing wear resistance to the composite in the adhesive wear regime.

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Additive Manufacturing of Lattice Structures for Heat Transfer Enhancement in Pipe Flow

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Abstract Additive manufacturing has added a new dimension to manufacturing technology. The Design for Additive Manufacturing (DFAM) principles provide guidelines for successful 3D printing. Several industrial applications utilize the cellular structures in AM for design improvement by light weighting, topology optimization, etc. Self-supporting behavior is the most desired characteristic for DFAM of cellular structures. In the present work, gyroid, star kagome and BCC cellular structures are evaluated for self-supporting behavior using Materialize Magics software. The lattice designs of different sizes are 3D printed and visually examined for defects. The lattice designs are introduced into a smooth circular pipe. Conjugate heat transfer analysis is done for different Reynolds numbers (1193–10736) using FloEFD to study heat transfer and pressure drop characteristics. All the lattice designs show heat transfer enhancement and higher pressure drop with respect to smooth pipe. Among all lattice designs, gyroid shows the highest heat transfer enhancement and highest pressure drop.

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A. Chakrabarti and M. Arora (eds.), *Industry 4.0 and Advanced Manufacturing*, Lecture Notes in Mechanical Engineering,
https://doi.org/10.1007/978-981-15-5689-0_21

Keywords Additive manufacturing · DFAM · Cellular structures · Gyroid · Star kagome lattice · Body-centered cubic lattice

Nomenclature

Nu	Nusselt number
Nu_{avg}	Average Nusselt number
h	Heat transfer coefficient (W/m^2 K)
D	Inside diameter of the pipe (m)
Re	Reynolds number
Pr	Prandtl number
L, x	Length of the pipe
c	1.4 for hydrodynamic fully developed flow
c	6 for hydrodynamic not developed flow
Q	Heat transfer in pipe with lattice
Q_b	Heat transfer in plain pipe
U_G	Gyroid unit cell size
T_G	Gyroid lattice surface thickness
k	Thermal conductivity (W/m K)
T_1	Water inlet temperature (K)
T_2	Water outlet temperature (K)
T_s	Surface wall temperature (K)
A_s	Surface area available for heat transfer (mm^2)
C_p	Specific heat of water at constant pressure
$\dot{m}$	Mass flow rate (kg/sec)
ΔP	Pressure drop in pipe with lattice
ΔP_b	Pressure drop in plain pipe
Ss	Star kagome lattice strut diameter
U_B	BCC unit cell size
S_B	BCC lattice strut diameter

1 Introduction

Additive manufacturing (AM) technology slices a CAD model into several layers, and the part is built in a layer-by-layer fashion. The usage of the AM was primarily for plastic rapid prototyping right from the inception of stereolithography in 1986 [1, 2]. Further, technological advancements as well as developments of new processes such as fused deposition modeling (FDM), selective laser sintering (SLS), selective laser melting (SLM) and laser metal deposition (LMD) have extended the capability of AM to production intent applications with wide range of metals and plastics

[1, 2]. The design freedom in AM enables manufacturing of complex parts easier when compared to conventional processes like casting, milling, drilling, etc. The Direct manufacturing capability enables AM to produce parts from the CAD models eliminating tooling and logistics costs involved in conventional processes.

DFAM [3–5] is one of the most important aspects in AM. Parts designed for AM must be carefully examined for DFAM rules [6–8] before proceeding for actual fabrication. Three important aspects in DFAM include part orientation and support material optimization to minimize the part build time, support material removal strategy after the part build and removal of powder remains after part build.

Recent innovations in AM product design include light weighting, [7, 9] topology optimization [10, 11], multifunctional optimization [12, 13], etc. Porous or cellular structures have come to limelight in most of the recent AM's product innovations. The cellular structures exhibit high strength, energy absorption properties and strong thermal and acoustic insulation properties [14]. The AM process is found most suitable for these structures since the interconnected network of cellular structures is self-supporting in nature. The self-supporting design is best suitable for AM because support material is eliminated during the part build. Several types of additive manufactured cellular structures are qualified for compression strength [15, 16] and implemented for structural applications. Additively manufactured cellular structures were used in very few thermal applications of injection molding tools [17].

Cellular structures play a vital role in heat transfer enhancement for thermal applications. The heat transfer in a closed circular pipe can be enhanced by active and passive methods. The active methods involve change in flow parameters, whereas passive methods involve the geometry modifications in the pipe. Several passive methods include twisted tape inserts [18], corrugations [19], extended surfaces [20], etc. In this work, an attempt has been made to examine the manufacturability of few cellular structures and their introduction into straight circular pipe for heat transfer enhancement.

2 Lattice Selection

In this work, lattice selection is done based on manufacturability in AM and heat transfer enhancement. By Newton's law of cooling, the convective heat transfer is directly proportional to surface area. By introducing lattice structures inside a plain pipe, the surface area is increased. Further, it will generate additional turbulence leading to heat transfer enhancement. Several types of lattice/cellular structures such as prismatic-type (honeycomb, triangulated etc.), truss-type (tetrahedral, BCC, pyramidal) and surface-type (triply periodic minimal surface (TPMS), gyroid, Schwarz primitive, etc.) are available. However, self-supporting behavior is very much essential to utilize them in internal flow applications. Gyroid, star kagome and BCC strut are considered for this study since these lattices possess different complexities in geometry, and all of them do not have overhang regions, favorable for DFAM.

3 Lattice Design and 3D Printing

3.1 Gyroid

A gyroid surface is a triply periodic minimal surface having zero mean curvature. The surface can be infinitely extended periodically along x-, y- and z-directions and can be represented by a unit cell. It was identified by Alan Schoen [21]. A close approximation of gyroid surface is given by Eqs. (1) and (2) [22, 23].

$$F(x, y, z) = t \tag{1}$$

$$F(x, y, z) = \sin\left(\frac{2\pi x}{a}\right)\cos\left(\frac{2\pi y}{a}\right) + \sin\left(\frac{2\pi y}{a}\right)\cos\left(\frac{2\pi z}{a}\right) + \sin\left(\frac{2\pi z}{a}\right)\cos\left(\frac{2\pi x}{a}\right) \tag{2}$$

where a is the periodicity of the gyroid and t is the time period.

The 3D models of gyroid lattice are created as shown in Fig. 1 by varying unit cell size and surface thickness. Table 1 presents different configurations of gyroid lattice considered for the study. All the configurations have the same shape, but they differ in size and thickness. Two configurations of 8 mm unit cell, having thickness 2 and 3 mm could not be modeled in CAD due to the complexity of curvature. Self-supporting

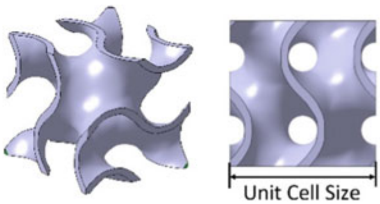


Fig. 1 Gyroid unit cell

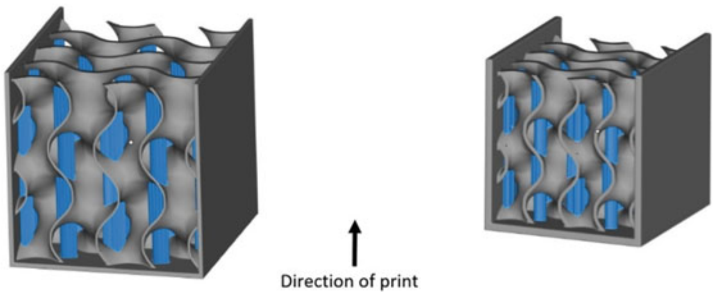
Table 1 Gyroid unit cell design configuration table

Unit cell size (mm)	Surface thickness (mm) T_G		
U_G	1 mm	2 mm	3 mm
8	*P*	*X*	*X*
16			
20	*P*		*P*
24			
32	*P*		*P*
40	*D*	*P*	*P*

P—specimens are printed, *X*—not possible in CAD, *D*—printed but defects are found behavior in 3D printing is examined by considering smallest, mid-sized and largest unit cell size designs. If these considered designs satisfy the self-supporting behavior, then designs of intermediate size will also satisfy the self-supporting behavior since the shape is identical in nature.

Figure 2 shows the 3D models of specimens analyzed for 3D printing. Two designs are considered for study: 40 mm unit cell with 1 mm thickness and 20 mm unit cell with 1 mm thickness. Support material recommendations are visualized in Materialize Magics software. The images shown in Fig. 2 reveal the need of supports at the overhang regions almost perpendicular to the direction of print, and these regions will be almost same irrespective of size of the gyroid unit cell. These support recommendations are ignored while 3d printing to evaluate self-supporting behavior.

The samples were printed with stainless steel material using Concept laser M2 3D printer. Figure 3 shows the images of 3D printed sample of 40 mm unit cell and 1 mm thick lattice. Distortion or thinning is observed due to inadequate support material. It is also noted that the region is same as the overhang regions as per the support material prediction in Materialize Magics. However, the same is not observed for rest of the designs as shown in Fig. 4. Hence, all the other designs except one with 40 mm unit cell and 1 mm thickness are favorable for self-supporting behavior in 3D printing.



(a) $U_G = 40$ mm, $T_G = 1$ mm (b) $U_G = 20$ mm, $T_G = 1$ mm

Fig. 2 Gyroid lattice support material visualization in Materialize Magics

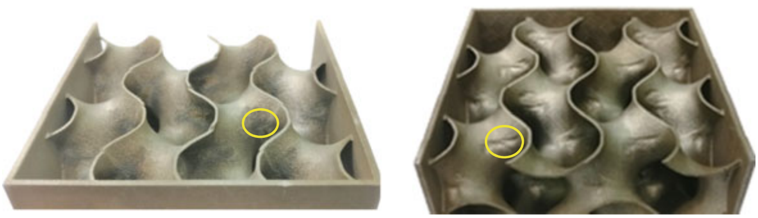


Fig. 3 3D printed sample of gyroid lattice: $U_G = 40$ mm, $T_G = 1$ mm

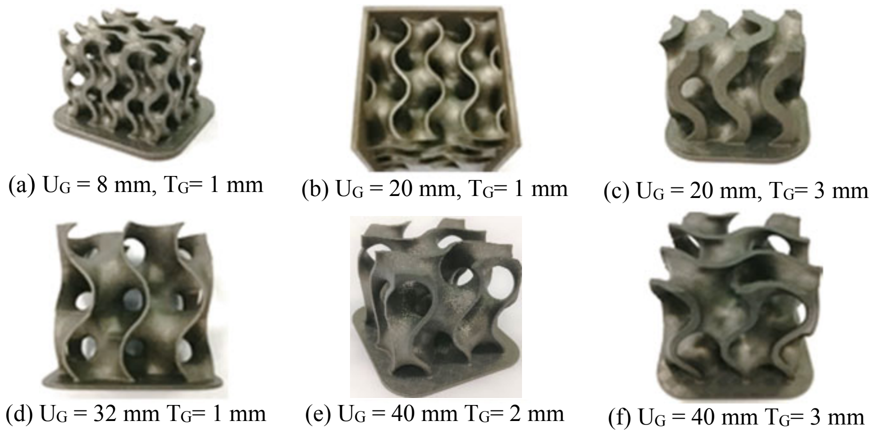


Fig. 4 3D printed samples of gyroid lattice

3.2 Star Kagome

Star kagome is a strut-based lattice. The unit cell shown in Fig. 5 resembles a star. All struts are connected by an angle. The unit cell is designed by varying strut diameter (1, 2 and 3 mm), and struts are connected by 45°. The diameter of 20 mm inscribing the star is considered for the study.

The design is varied to have changes only in size but not affecting the shape. Table 2 shows the design configuration table. Two design configurations ones with strut diameter 1,3 mm are analyzed in Materialize Magics. Figure 6 reveals that the regions of strut intersections require negligible support material, and they can be ignored in 3D printing. No defects were observed in 3D printed specimens of both

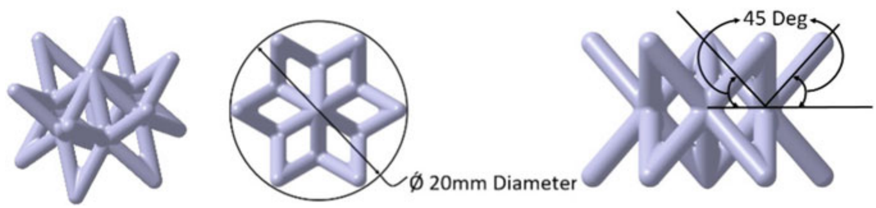


Fig. 5 Star kagome unit cell

Table 2 Star kagome lattice design configuration table

Strut Angle	Strut diameter (mm) S_S		
(degree)	1 mm	2 mm	3 mm
45	*P*		*P*

P—specimens are printed

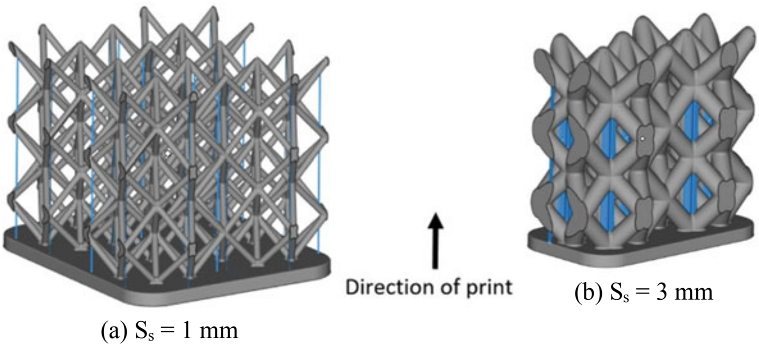


Fig. 6 Star kagome lattice support material visualization in Materialize Magics

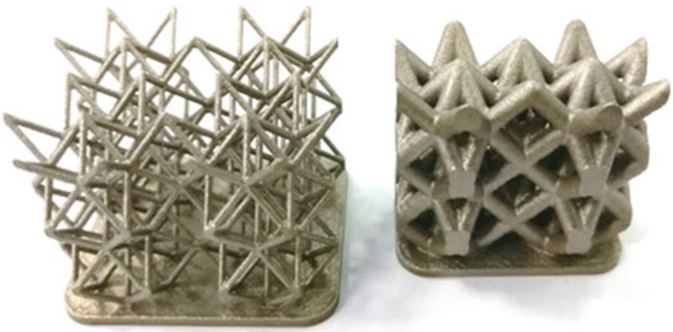


Fig. 7 3D printed samples of star kagome lattice

the lattice designs of extreme size as shown in Fig. 7. So, all the designs satisfy the self-supporting behavior in 3D printing.

3.3 Body-Centered Cubic (BCC) Lattice

BCC lattice is also a strut-type lattice as shown in Fig. 8. The struts occupy the four diagonal positions of a cube. The unit cell is designed by varying the strut diameter

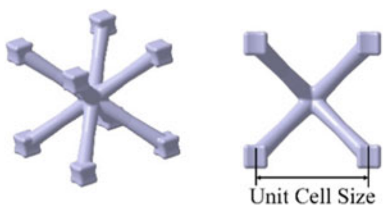


Fig. 8 BCC unit cell

Table 3 BCC unit cell design configuration table

Unit cell size (mm)	Strut diameter (mm) S_B		
U_B	1 mm	2 mm	3 mm
5	*P*	*X*	*X*
10			
15	*P*		*P*

P—specimens are printed, *X*—not possible in CAD

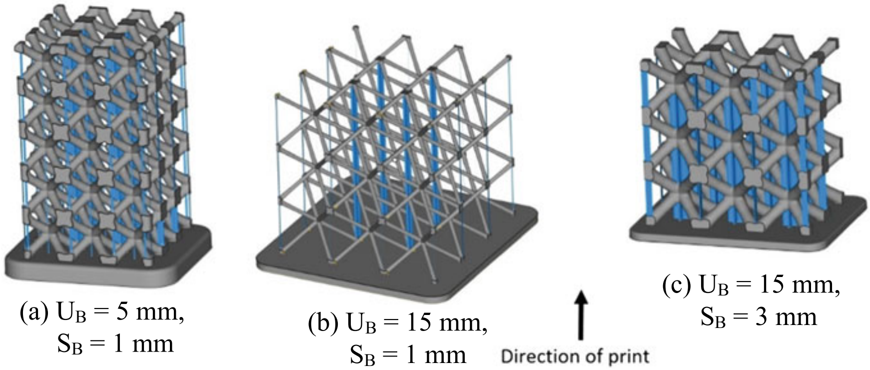


Fig. 9 BCC lattice support material visualization in Materialize Magics

(1, 2 and 3 mm) and unit cell size from 5 to 15 mm. The designs are created by varying unit cell size without affecting the shape. Table 3 shows the design configurations considered for the study. The two design configurations of 5 mm unit cell with 2, 3 mm strut diameter are not possible to model in CAD due to complexity in providing the fillets at the strut intersection regions.

Figure 9 shows the support material requirements at the strut intersecting regions. The support material requirement is almost negligible, which is most favorable for self-supporting behavior in 3D printing. Figure 10 shows 3D printed samples of BCC lattice. No significant defects like distortion and thinning were observed.

4 Conjugate Heat Transfer (CHT) Analysis

CHT analysis is performed for a straight circular pipe to study effect of introduction of lattice structures on heat transfer and pressure drop characteristics. The methodology and results of CHT analysis are presented in the following sections.

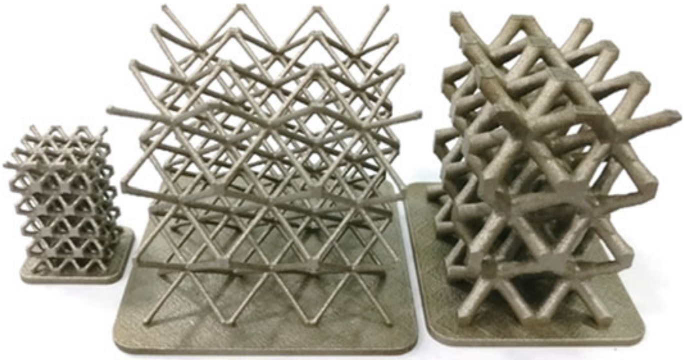
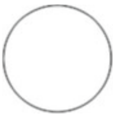
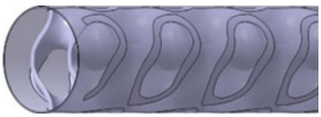
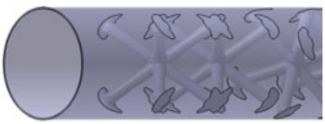


Fig. 10 3D printed samples of BCC strut lattice structure

4.1 Geometry

For CHT analysis, four geometries are considered. The baseline design consists of a smooth straight pipe with 20 mm diameter and 0.25 mm thickness. The length of pipe considered for analysis is 500 mm. The lattice designs are integrated to smooth pipe of 20 mm diameter (baseline design). Table 4 shows CAD models of lattice designs considered for analysis and surface area comparison. Star kagome and BCC

Table 4 Pipe configurations considered for CHT analysis

Design configuration	Cross section	Longitudinal section	Surface area (mm^2)
Baseline			31,416
Star Kagome $S_s = 2$ mm			59,068
Gyroid $U_G = 20$ mm, $T_G = 1$ mm			73,848
BCC Strut $U_B = 15$ mm, $S_B = 2$ mm			44,906

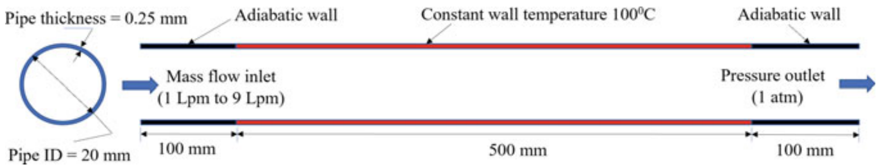


Fig. 11 Boundary conditions of CHT analysis

unit cells are arranged along the length of the pipe and rotated about the pipe axis to increase the flow path favorable for effective heat transfer. All the configurations offer higher surface area than baseline. Gyroid configuration is found to have the highest surface area.

4.2 Solver Setup and Boundary Conditions

CHT analysis is performed using FloEFD solver integrated into CATIA. The effect of lattice structures on heat transfer and pressure drop is studied at different Reynolds numbers (1193–10736). Water is used as a working fluid. The flow is assumed to be hydrodynamically fully developed at inlet. The pipe material considered for the analysis is stainless steel. Extensions are provided at inlet and outlet to avoid backflow. The boundary conditions are shown in Fig. 11.

4.3 Validation for Baseline Design

The CFD results for baseline design are validated using correlations available in the literature for both laminar and turbulent flow through pipe given in Eqs. (3)–(5) [24]. Figure 12 shows that the water outlet temperature predicted by CHT analysis is in close agreement with correlations.

Laminar condition

$$Nu = \frac{hD}{k} = 3.66 + \frac{0.065\mathrm{Re\,Pr}\,\frac{D}{L}}{1 + 0.04\left(\mathrm{Re\,Pr}\,\frac{D}{L}\right)^{2/3}},\ \mathrm{Pr} > 0.7 \tag{3}$$

Turbulent condition

$$\mathrm{Nu} = 0.036\mathrm{Re}^{0.8}\mathrm{Pr}^{0.33}(D/L)^{0.055};\ 10 < L/D < 400 \tag{4}$$

$$\mathrm{Nu}_{\mathrm{avg}} = \frac{hD}{k} = \mathrm{Nu}\left(1 + \frac{c}{x/D}\right);\ \frac{x}{D} > 10 \tag{5}$$

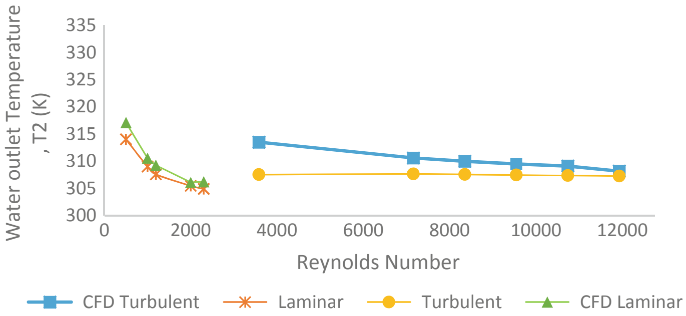


Fig. 12 CFD validation for baseline

The outlet temperature (T_2) is calculated by trial and error method by using energy balance equation.

Heat lost by circular pipe wall (uniform wall temperature) = Heat gained by water

$$hA_s\left(\frac{(T_2 - T_s) - (T_s - T_1)}{\ln[(T_2 - T_s)/(T_s - T_1)]}\right) = \dot{m}C_p(T_2 - T_1) \tag{6}$$

4.4 Heat Transfer Rate

Heat transfer rate is found to increase with Reynolds number as shown in Fig. 13a.

Introduction of structures in pipe increases both surface area available for heat transfer as well as creates turbulence. Hence, heat transfer rate increases, resulting in higher water outlet temperature. Among all lattice structures, heat transfer rate is highest for gyroid and lowest for BCC.

4.5 Pressure Drop

The pressure drop versus Reynolds number curves are shown in Fig. 13b. The introduction of structures creates obstruction for the fluid flow. Pipe with structures results in higher pressure drop compared to plain pipe. Gyroid lattice structure shows the highest pressure drop.

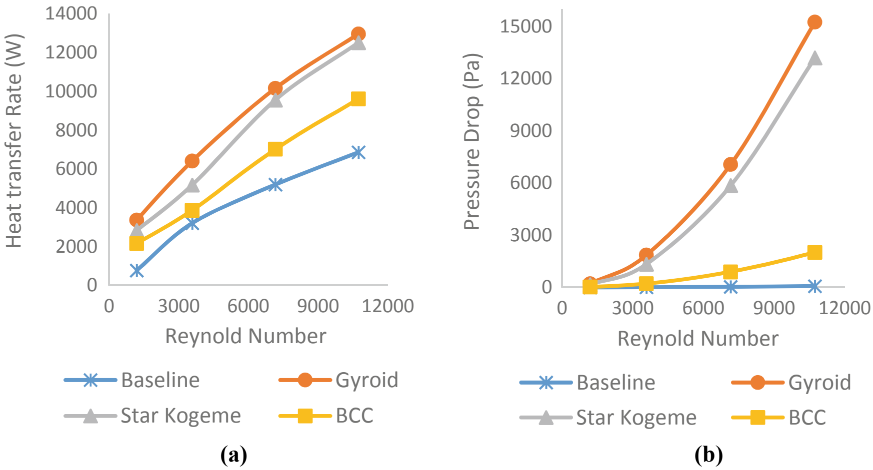


Fig. 13 **a** Heat transfer rate versus Reynolds number, **b** pressure drop versus Reynolds number

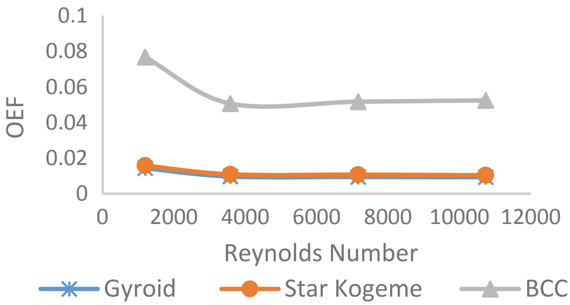
4.6 Overall Enhancement Factor (OEF)

The introduction of lattice structures in the plain pipe results increase in heat transfer. However, the pressure drop also increases. The overall enhancement factor is defined to assess how effectively heat transfer occurs at the cost of pressure drop.

$$\text{OEF} = \frac{Q/Q_b}{\Delta P/\Delta P_b} \tag{7}$$

Figure 14 shows variation of OEF for all the designs with respect to Reynolds number. All the designs have very less OEF compared to baseline value of 1. This is because of the pressure drop. An ideal design should give better heat transfer with no increase in pressure drop which is practically impossible since lattice structures obstruct the flow. Among all designs, BCC exhibits good heat transfer with less pressure drop. The gyroid and star kagome behave almost the same.

Fig. 14 Overall enhancement factor for all designs



5 Conclusions

The gyroid, star kagome and BCC lattice structures are successfully evaluated for self-supporting behavior in 3D printing for different sizes of lattice. The support material recommendations by Materialize Magics were not considered for printing the samples to evaluate the self-supporting behavior. The 3D printed samples are visually inspected for defects like thinning and distortion. The images reveal that visual defects were observed in the gyroid lattice of 40 mm unit cell size with 1 mm thickness, and all other designs were 3D printed with no significant defects. The lattice designs were introduced into straight circular pipe of 20 mm diameter and analyzed for the heat transfer enhancement using CHT analysis. The results show that all the lattice designs show better heat transfer than the baseline. Pressure drop is unavoidable when lattice structures are introduced in the flow. The usage of lattice design is recommended for the industrial applications where pressure drop or pumping power is not a concern. Certain industrial applications demand effective heat transfer with size restrictions, so increasing the pipe diameter is highly restricted. Therefore, lattice structures manufactured by AM can be the best solution.

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Influence of Workpiece Height on Induction Heating Process for Printing 3D Metal Structures

Hemang Kumar Jayant and Manish Arora

Abstract Induction heater is used in industry for heating and melting metals. It can potentially be used for printing metals structures in three dimensions (3D). In this paper, we present an experimental and simulation study on influence of workpiece height during heating and melting of lead-free solder (Sn99Cu1) using a zero-voltage switching-based induction heater. 2D axis-symmetric finite element method (FEM) simulations are conducted to study the influence of solder workpiece height relative to induction coil height. Results are compared with available theoretical models, used for calculating the power transfer to the solder. Three solder workpieces of varying height (45, 65, and 85 mm) are heated up to the melting point, and their temperature profile is measured using embedded thermocouple. The power transfer and heating rate from the experimental results, simulations, and theoretical model are compared with each other. While the simulation and experimental results match closely over the range of workpiece height covered, theoretical results match only for the case where height of workpiece is equal to height of induction coil. These differences are attributed to non-uniform magnetic flux density across the workpiece which was not considered in theoretical model. This study provides more insights into selection of efficient workpiece geometry for 3D metal printing using induction heating process.

Keywords Induction heater · Solder (Sn99Cu1) · Power transfer · FEM simulation · Eddy current · Magnetic flux density · Heating rate

1 Introduction

Additive manufacturing is a key component of Industry 4.0 which enables direct manufacturing of 3D complex structures using a wide variety of materials [1].

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A. Chakrabarti and M. Arora (eds.), *Industry 4.0 and Advanced Manufacturing*, Lecture Notes in Mechanical Engineering,
https://doi.org/10.1007/978-981-15-5689-0_22

Printing three-dimension (3D) metal structures is an emerging field in industrials and non-industrial areas [2]. These printing techniques require melting of metals using high power source, such as laser [3], resistive band heater [4, 5], arc base welding [6], and induction heating [7]. For conductive materials, the induction heating process is a fast and efficient method due to local heating of the workpiece. Though the induction heating process is widely used for melting metals in industries, it is not yet explored for metal additive manufacturing. Using an induction heater, one can even melt the high melting point metals such as Titanium. [8]. Apart from melting the metals, induction heater (IH) coil can also be used to generate metal droplet on demand using magnetohydrodynamic phenomenon [9]. High-frequency IH (>10 kHz) is used for the application of heating thin workpieces, whereas low-frequency IH is used for the thick workpiece. IH are available with a fixed frequency, user selectable variable frequency, or natural resonating frequency [10, 11]. Fixed frequency IH are less efficient as compared to the IH which works on the natural resonating frequency of induction coil and workpiece. The geometry of the workpiece also is an important factor in power transfer from induction coil to workpiece especially in case of naturally resonant IH. Nagaoka coefficient is used to determine the effect of induction coil diameter to induction coil height on the overall power transfer [12]. Here, induction coil height is assumed to be same as workpiece height. Modified Nagaoka coefficient can be used for calculating accurate power transfer by considering the ratio of workpiece diameter to induction coil diameter [13].

To calculate the power transfer to the workpiece, the magnetic flux density in and around the workpiece can be simulated using finite element method (FEM) [14, 15]. Though these simulations can be modelled in 3D or 2D, IH are mostly modelled as a 2D axisymmetric problem to reduce the complexity and processing time. Tavakoli et al. developed a 2D axis-symmetric model to simulate the influence of workpiece height on induction heating process [16]. Comparison of simulated power with experimental and theoretical models for varying workpiece height is not reported in the literature.

In this paper, we have studied the behaviour of zero-voltage switching (ZVS)-based IH on the workpiece (Solder-Sn99Cu1) having three different heights (45, 65, and 85 mm). The temperature profile of the workpiece is measured using embedded thermocouple and further used for calculating the heating rate of workpiece. Power transfer and heating rate of workpieces are also determined theoretically using modified Nagaoka coefficient. FEM-based 2D axis-symmetric simulations are conducted using COMSOL to simulate the power transfer, magnetic flux density, and eddy current density in the workpiece. At last, for solder workpieces of varying height, the power transfer using experimental results, simulations, and theoretical model are compared.

2 Experimental Setup and Temperature Control

2.1 Experimental Setup Description

The IH setup consists of a high-frequency induction heater (IH) based on a zero-voltage switching (ZVS) circuit using two Metal Oxide Semiconductor Field Effect Transistor (MOSFET) and is described in detail in our earlier work [17]. The ZVS circuit allows to oscillate the current between the induction coil and capacitors at its natural frequency (f) given as Eq. (1).

$$f = \frac{1}{2\pi\sqrt{LC}} \tag{1}$$

where L is the inductor value in Henry, and C is the capacitor value in Farad. For this study, IH setup is modified to accommodate higher capacitance (1.32 µF) and solid core induction coil. The copper-coil inductor consists of ten turns in a helical shape, with a mean inner coil diameter of 19.75 mm, the height of 65 mm, where the copper wire diameter is 5 mm (see Fig. 1).

In this setup, with the workpiece, the frequency of this alternating current is approximately 171 kHz. This high-frequency alternating current in the induction coil leads to generate an alternating magnetic field inside the coil at the same frequency

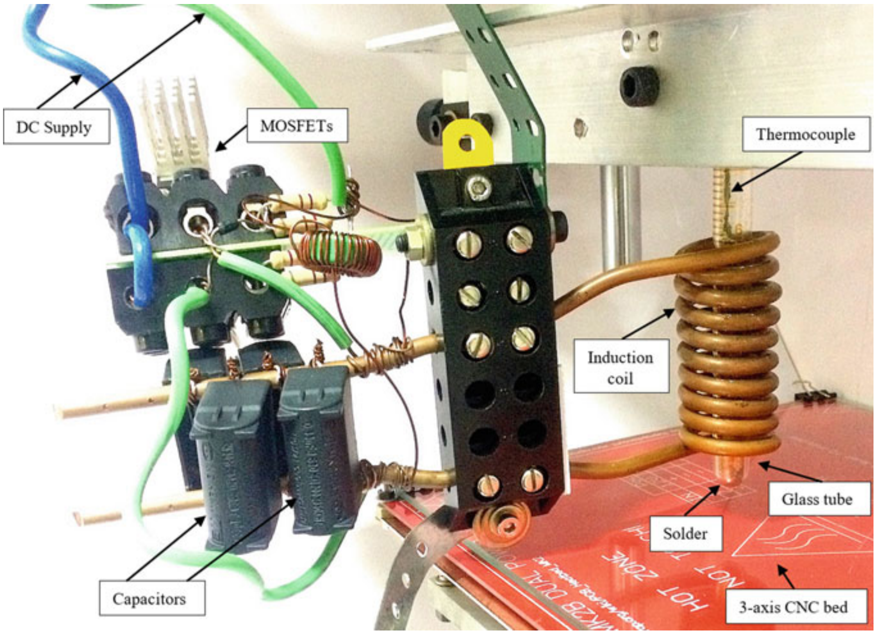

Fig. 1 Experimental setup of ZVS induction heater setup with solder kept inside glass tube

Table 1 Solder (Sn99Cu1) and IH setup properties

Name	Symbol	Value
Solder resistivity	ρ	1.26e-7 Ωm [18]
Solder height	h	45, 65 and 85 mm
Solder radius	r	4e-3 m
Solder melting point	T_{m}	227 °C
Specific heat coefficient of solder	C_{ps}	210 J/kg K
Specific heat coefficient of glass	C_{pg}	830 J/kg K
Borosilicate glass height	h_{g}	45, 65 and 85 mm
Induction coil height	L	65 mm

given by Eq. (1). As the metal workpiece is present in the coil, these alternating magnetic fields pass through the workpiece. To oppose this magnetic field, the workpiece generates an alternating magnetic field inside it, in the opposite direction. As the workpiece is conductive, these induced magnetic fields in the opposite direction generate an eddy current inside the workpiece. Due to skin effect, most of the eddy current flows through the surface of the workpiece. The penetration depth (δ) of eddy current flow in the workpiece depends on the frequency of the alternating current, workpiece resistivity (ρ), and workpiece relative permeability (μ_r), given by Eq. (2).

$$\delta = \sqrt{\frac{\rho}{f_c \pi \mu_r \mu_o}} \tag{2}$$

where μ_o is the permeability of free space. Due to Joule heating, these eddy currents lead to rise in the temperature of workpiece. We have used a low-melting point alloy (Solder-Sn99Cu1) as a workpiece. The solder properties used in the experiments are shown in Table 1.

2.2 *Temperature Measurement and Control*

To measure the temperature profile in real time, a K-type thermocouple was inserted in the solder. We have used a compact DAQ system (NI-CDAQ-9185) with temperature module (NI-CDAQ-9211) and digital input/output module (NI-CDAQ9403) to measure thermocouple data and to communicate control signals, respectively. Temperature data was recorded at a rate of 1 Hz using LabVIEW (National Instruments Inc) (see Fig. 2). In these experiments, the IH was kept on till the workpiece started melting.

The solid solder material is loaded inside the borosilicate glass tube up to a height of 45 mm, 65 mm, and 85 mm. The glass tube has ID of 8 mm and OD of 10 mm. The IH and workpiece were kept stationary during these experiments. In this paper, we have only observed the influence of workpiece height on induction heating process.

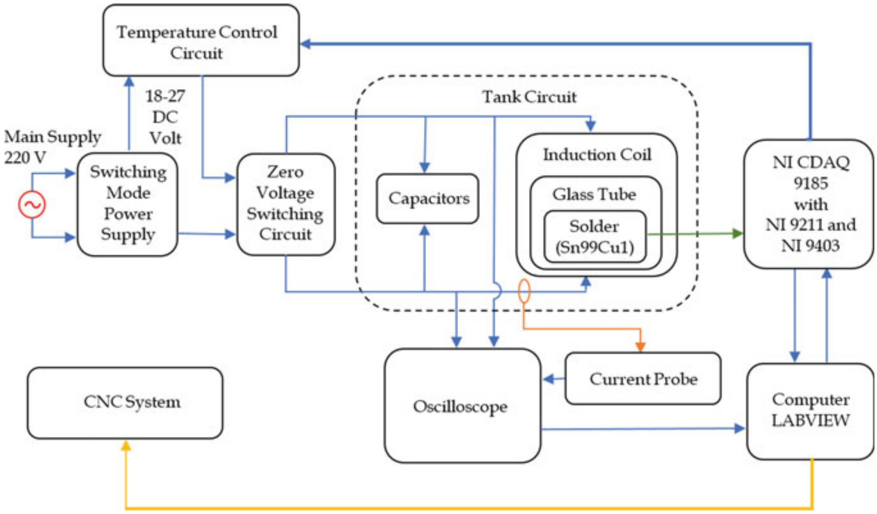

Fig. 2 Block diagram of ZVS induction heater setup with temperature control

3 Influence of Height: Theoretical and Numerical Modelling

3.1 Theoretical Modelling Description

The geometry and material property of the workpiece play an important role during the induction heating process. As the temperature of solder (workpiece) increases, the material property changes with it, leading to change in amount of induced eddy current, which further change the heating rate of workpiece. Theoretically, while calculating the heating rate, we assume that the induction coil is of infinite length and having a uniform magnetic flux density in the workpiece. To study the effect of workpiece height on the induction heating process, we have taken three different heights of workpiece. The theoretical power (P_{th}) transferred to the workpiece depends on the applied magnetic flux density (B), applied current (I_o), and frequency (f) of current in the coil, cross-sectional surface area of workpiece (πr^2), workpiece height (h), induction coil height (L), and modified Nagaoka coefficient (k) for the geometry of workpiece, given as [19]:

$$P_{\text{th}} = \frac{(N I_o k \pi r)^2 \mu_o \mu_r Q f h}{L^2} \tag{3}$$

where Q is function of penetration depth and workpiece radius, defined as $Q = \{2/(1.23 + (2r/\delta))\}$. In our experiments, Q is equal to 0.1011. For measuring the heating rate of workpiece, we divide the power transfer by combined heat capacity of solder and glass (see Eq. 4). Experimentally, the power transferred to workpiece can also be calculated using the heating rate of workpiece:

$$P_e = (m_s C_{ps} + m_g C_{pg}) \frac{\partial T}{\partial t} \tag{4}$$

where P_e is the power transferred measured during experiment using temperature profile, m_s is the mass of solder, C_{ps} is the specific heat coefficient of solder, m_g is the mass of glass, C_{pg} is the specific heat coefficient of glass tube, $\partial T/\partial t$ is the rate of change of temperature. In this paper, we have not accounted for convective and radiative losses as they are negligible. With change in workpiece height, the induced magnetic flux density will also change in experiments, thus leading to variation in the power transfer and heating profiles. These changes are also not captured in the above theoretical model.

3.2 Numerical Modelling Description

We have modelled IH as a 2D axis-symmetric system in COMSOL (Version 5.3) to study the induction heating process with varying workpiece height. We conducted a frequency stationary study with the helical coil of ten turns, which is modelled as an arrangement of ten rings placed along the axis of the workpiece. The workpiece is placed at the centre of induction coil. The applied coil current, frequency, and other material properties of workpiece are fixed during the simulation. This finite element method (FEM)-based simulation can determine the magnetic flux density generated in the workpiece by applying an alternating current in the coil, by solving Maxwell equations:

$$\nabla \times H = J + \frac{\partial D}{\partial t} \tag{5}$$

$$\nabla \times E = -\frac{\partial B}{\partial t} \tag{6}$$

$$\nabla . D = \rho_e \tag{7}$$

$$\nabla . B = 0 \tag{8}$$

Here, H is the magnetic field intensity, E is electric field intensity, D is the electric displacement, B is the magnetic flux density, J is the current density, ρ_e is the electric charge density. As the induced eddy current density norm $\overrightarrow{J_i}$ represents the power transfer to the workpiece, to measure the simulated power (P_s) transfer, we have defined an integral equation given as

$$P_s = \oint_v \rho \overrightarrow{J_i}^2 \partial V \tag{9}$$

Where V is the surface volume of the solder in glass tube. Inbuilt fine triangular meshing procedure using boundary conditions has been used to mesh the geometry. The smallest element size was 8×10^{-5} m which is enough for capturing the sharp gradient in the outer layer of the workpiece. Also, a boundary layer mesh is applied on the surface of workpiece and coil having the size less than the penetration depth to capture the electrical and magnetic flux density in the workpiece.

4 Result and Discussions

We have conducted an experiment with three different heights of solder (45, 65 and 85 mm) as a workpiece with a fixed height of induction coil (65 mm). Without the solder (load), the frequency is measured as 162.1 kHz approximately, while with the solder (45, 65, and 85 mm), the frequency is measured as 171.6 kHz (change of 5.8%). At this resonating frequency, by changing the workpiece height, the initial alternating current is measured as 104 amperes. Magnetic flux density in the workpiece is directly proportional to the applied current in the coil. For simulation, we have used FEM-based 2D axisymmetric modelling. Simulation was carried out using experimentally measured alternating current amplitude and frequency.

For the case of workpiece height of 45 mm and induction coil current of 104 A, a non-uniform magnetic flux density is observed. At the edges, magnetic flux density is 0.024 T, whereas for the rest of the workpiece, it is about 0.016 T, as shown in Fig. 3b. Whereas, Fig. 3a shows the uniform current density ($\overrightarrow{J_i}$) generated throughout the workpiece with a value of 4.5×10^7 A/m^2. Using the eddy current density shown in the simulation, the heating rate of workpiece is calculated using Eq. (9) and found to be 5.57 °C/s.

For the case of workpiece height of 65 mm and the induction coil current of 104 A, a uniform magnetic flux density approximately 0.016 T is observed throughout the workpiece, as shown in Fig. 4b. Whereas, Fig. 4a shows the non-uniform eddy current density norm ($\overrightarrow{J_i}$) generated in the workpiece with the highest value at the height centre as 4.5 × 107 A/m^2, and at the top and bottom edges of the workpiece as 2.8 × 107 A/m^2. Using Eq. 9, heating rate is found to be 4.49 °C/s. The heating rate of the workpiece is reduced, even though the total power transferred is higher in this case as compared to the previous case (height = 45 mm). This reduction in heating rate is attributed to an increase in workpiece height and mass.

For the case of workpiece height of 85 mm and the induction coil current of 104 A, again a non-uniform magnetic flux density is observed as shown in Fig. 5b. At the top and bottom edge of the workpiece, magnetic flux density of 0.0037 T is measured in simulations, whereas for the rest of the workpiece, it is about 0.016 T. The same we can see in Fig. 5a, where, the non-uniform eddy current density generates mostly

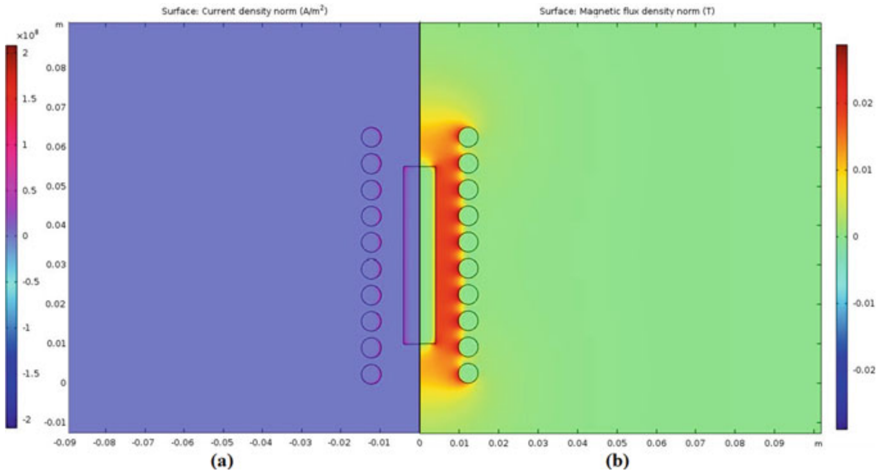

Fig. 3 For the workpiece height of 45 mm with applied current of 104 A. **a** shows the current density norm in the solder and coil, **b** shows the magnetic flux density norm in the solder, air, and coil. The magnetic flux density is high at the edges of the solder workpiece

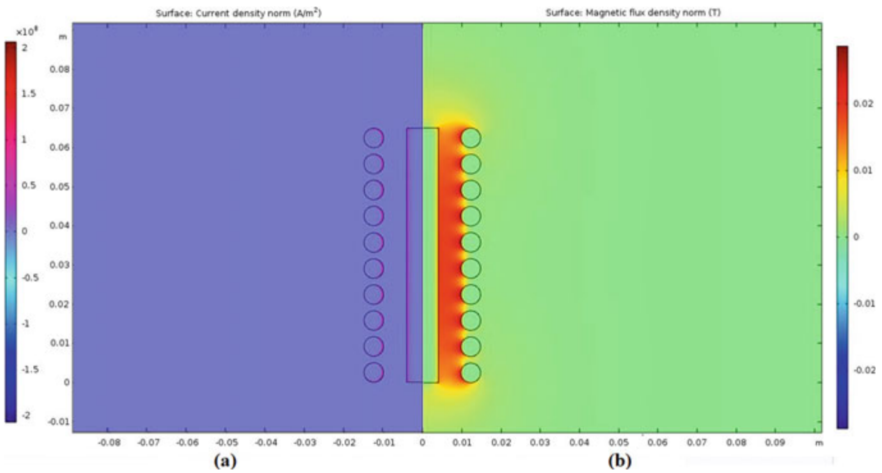

Fig. 4 For the workpiece height of 65 mm with applied current of 104 A. **a** shows the current density norm in the solder and coil, **b** shows the magnetic flux density norm in the solder, air, and coil. The magnetic flux density is uniform throughout the solder height

in the region of induction coil. At the height centre, eddy current density is 4.5 × 107 A/m^2, whereas at the top and bottom edges, it is only 7 × 106 A/m^2. Using Eq. (9), heating rate is found to be 3.47 °C/s. The heating rate is less as compared to the previous simulation result, due to an increase in workpiece mass.

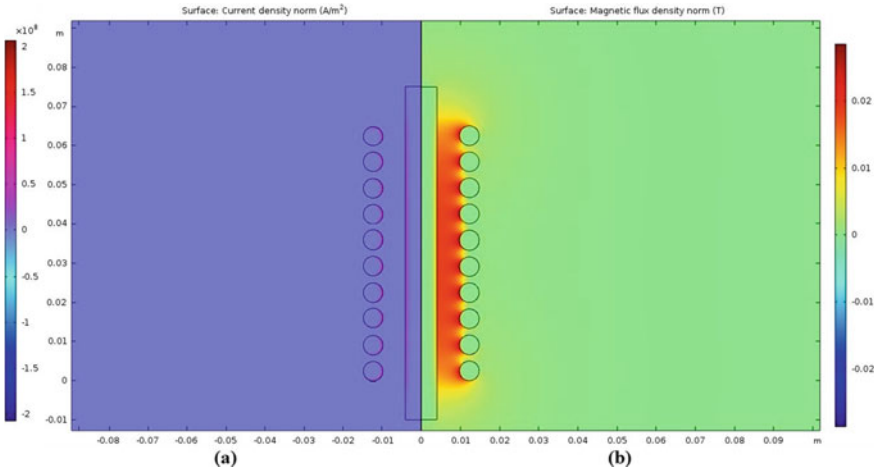

Fig. 5 For the workpiece height of 85 mm with applied current of 104 A. **a** shows the current density norm in the solder and coil, **b** shows the magnetic flux density norm in the solder, air, and coil. The magnetic flux density is weak at the edges of the solder workpiece

The temperature of the workpiece was measured using embedded thermocouple for all three experiments. During the experiment, the workpiece was heated from the initial temperature (31 °C) to its melting point (227 °C). For the case workpiece of 45 mm height, the workpiece was melted in approximately 36.07 s. During these experiments, we have observed, with increasing the workpiece height, the workpiece heating rate decreases. In the case of workpiece of height 65 mm, the melting time is measured as approximately 50.17 s. In the case of 85 mm workpiece height, the melting time extends even more due to (a) increase in workpiece mass and (b) higher convective and radiative losses attributed to the larger surface area. The overall time taken to melt 85 mm workpiece is 93 s. As in the third case, the heating rate is nonlinear towards the end, to measure the power transfer, the linear part of the heating profile is considered (see Fig. 6). The measured heating rate for workpieces of height 45, 65, and 85 mm is found to be 5.45, 4.04, and 2.95 °C/s, respectively.

For all three workpiece heights, Table 2 shows the power transfer from induction coil to the workpiece, using simulations, measured temperatures heating profiles, and theoretical model. For the workpiece of height 85 mm, simulation and theoretical model show the maximum power transfer from the induction coil to the workpiece. Whereas, experimentally calculated results from measured temperature profiles show the maximum power transfer for the case, where the induction coil height is equal to workpiece height.

Using Eq. (3), the theoretical power transfer is calculated for all three different workpieces heights. The formula is based on the geometry, frequency, applied current, and material property of workpiece. Surprisingly, the theoretical heating rate of all three workpieces is found to be, 4.51 °C/s. This result is explained by the fact that theoretically power transfer is directly proportional to the workpiece volume which

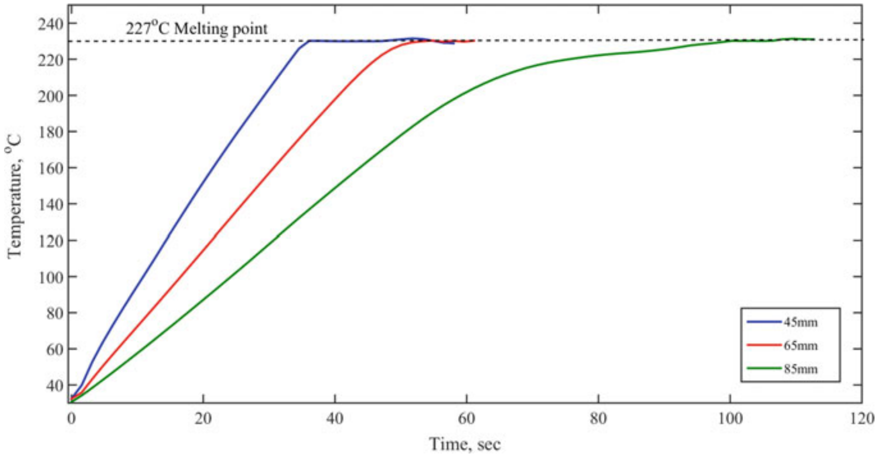

Fig. 6 Measured heating profile of workpiece with height of 45, 65, and 85 mm using thermocouple. The higher slope shows the fast heating of workpiece

Table 2 Power transfer from induction coil to solder using simulation, experiments, and theoretical model

Power measurement method	Solder height		
	45 mm	65 mm	85 mm
Simulation (P_s)	38.05 W	44.24 W	44.57 W
Experiment (P_t)	37.26 W	39.82 W	37.98 W
Theoretical (P_{th})	30.77 W	44.39 W	58.05 W

is proportional to its heat capacity, thus giving a constant heating rate. Note that, the theoretical equation assumes the magnetic flux density remains constant along with the height of the workpiece. In reality and simulations, the magnetic flux density is non-uniform, at least for the cases where the height of the workpiece is different from induction coil height. The measured heating rate using experimental temperature profiles, theoretical equation, and simulations is shown in Table 2.

As shown in Fig. 7 and Table 3, these workpiece heating rates show that simulated and experimental results are approximately matching with each other for different workpiece height, whereas the theoretical equations show a constant heating rate irrespective of workpiece height, due to the assumption of uniform magnetic flux density across the workpiece height. For the workpiece height of 65 mm, the simulated heating rate is equal to the heating rate calculated by theoretical formula as the magnetic flux density is approximately constant along the height of the workpiece. For all three cases, the simulated heating rate is somewhat higher than the experimentally measured heating rate as simulations neglect the radiative and convective losses.

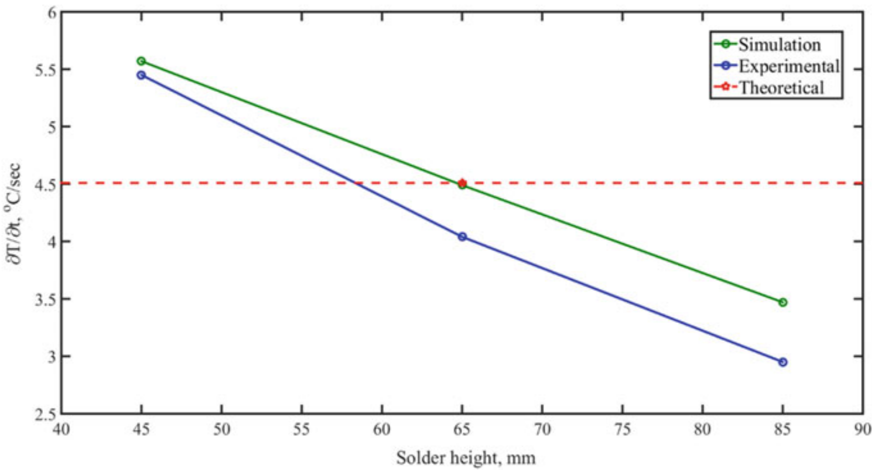

Fig. 7 Heating rate of solder for 45, 65, and 85 mm height using simulations, experiments, and theoretical calculations, where the induction coil length is 65 mm

Table 3 Heating rate of solder using simulations, experiments, and theoretical model

Method	Solder height		
	45 mm	65 mm	85 mm
Simulation ($\partial T/\partial t$)	5.57 °C/s	4.49 °C/s	3.47 °C/s
Experiment ($\partial T/\partial t$)	5.45 °C/s	4.04 °C/s	2.95 °C/s
Theoretical ($\partial T/\partial t$)	–	4.51 °C/s	–

5 Conclusion

Three different height solder (Sn99Cu1) workpieces were heated using an induction heater for studying the behaviour of heating rate and power transfer from induction coil to the workpiece. The influence of workpiece height on its heating rate is observed using 2D axis-symmetric finite element method (FEM) simulation, experimentally measured temperature profile, and theoretical equations. The simulation shows that, only in the case, when workpiece height is equal to induction coil height, the workpiece experiences a constant magnetic flux density along its height. Otherwise, the magnetic flux density is non-uniform along the workpiece height. Theoretical approach assumes uniform magnetic flux density and therefore is only valid for case where workpiece height is equal to induction coil height. Total power delivered to the workpiece increased with increase in its height till it matches with induction coil height. With further increase in work height, the increase in power transfer is negligible.

Both experiments and simulations show that the heating rate increases with the decreasing workpiece volume. Highest heating rate is observed for the smallest workpiece height. Furthermore, heating rates calculated from FEM simulations match closely with experimentally observed heating rates for all three cases. Theoretical framework needs to be further developed to calculate power transfer when workpiece height is not equal to induction coil height.

For the application of using induction heater in the 3D metal printer, this study will provide further insight for most suitable workpiece geometry for efficient heating. In this paper, we have only focused on the influence of workpiece height alone on induction heating process. In future, we would extend the theoretical model for calculating the heating rate of the workpiece as a function of workpiece height with induction coil height. Also, we will use the study of heating rate, to design a 3D metal printer.

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Controls, Autonomous Systems and Robotics

Zone-Based Path Planning of a Mobile Robot Using Genetic Algorithm

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Abstract Path planning is one of the widely studied problems in mobile robotics, which deals in finding an optimal path for a robot. To generate a collision-free path for a robot in an environment by satisfying certain constraints is a complex task. So, path planning is an NP-hard problem. In this paper, we present a new formulation of the path planning problem for a mobile robot by introducing zones which are neighbors to the static obstacles, through which a robot can pass avoiding the collisions. Our proposed model has an advantage of shrinking the search space which in turns reduces the computational complexity. We consider the minimization of the travel distance of a robot as the main objective to find a feasible path. We implement a genetic algorithm (GA) as a solution technique and compare it with two other well-studied meta-heuristic algorithms, viz. Tabu Search and Simulated Annealing. Further, we incorporate a modified mutation operation in all three algorithms to replace a zone from the reduced search space to generate a new potential solution. The simulations for different environments and comparative analysis using obtained results show that GA performs better than the other two approaches.

Keywords Mobile robots · Path planning · Genetic algorithm · Collision avoidance

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A. Chakrabarti and M. Arora (eds.), *Industry 4.0 and Advanced Manufacturing*, Lecture Notes in Mechanical Engineering,
https://doi.org/10.1007/978-981-15-5689-0_23

1 Introduction

With the advancement in robotics, mobile robots are employed in several domains like manufacturing, assembling, space exploration, nuclear power plants, and mobile systems. Path planning is one of the critical issues in the field of mobile robots, which has attracted many researchers to design efficient solution techniques [1]. Here, the primary goal is to find the shortest feasible path for a robot, avoiding collisions with the obstacles in an environment. Therefore, it can be modeled as an optimization problem subject to certain constraints. The problem becomes very complex with an increase in the size of the environment which may lead to the formation of several possible paths. Thus, a collision-free path planning problem belongs to the category of NP-hard problems [2]. There are many studies on the path planning problem using various techniques such as random trees, roadmaps, cell decomposition, potential fields, and grid-based A* algorithm [3]. Each of these techniques has pros and cons depending upon the type of the domain where it is employed. Most of such methods bear a limitation of finding only one solution, which may not be optimal or shortest even for a static environment [4]. Due to the complexity of the problem, traditional optimization techniques become incompetent and intractable to solve it [2].

Heuristic approaches like evolutionary algorithms (EAs) are proved to be a powerful tool as they are simple to design robust solution methods for path planning problems [5]. As a meta-heuristic technique, genetic algorithms (GAs) have been widely studied for several optimization problems including mobile robot path planning problem [6]. Manikas et al. [1] proposed a GA-based navigation technique for an autonomous robot to traverse the path. An environment with static and dynamic obstacles was designed by Mahjoubi et al. [7] and formulated a solution technique using GA to avoid collisions. Similarly, to design a path for a robot, Song et al. [8] used a grid representation of an environment to simulate their GA-based solution technique along with a Bezier curve. A new binary encoded matrix was developed by Patle et al. [9] for GA to generate a path together with an optimum controller method. A new selection approach including the robot's speed into the encoding of the solution was designed by Wang et al. [10]. They developed a path planning approach using GA to find a near optimal solution avoiding the obstacles. In [4], Tuncer et al. integrated a new mutation operator into a GA-based solution to find an optimal path in a grid-based environment. Despite several studies, the path planning problem still needs to be formulated efficiently to decrease the complexity of search space. Further, it also requires a tool to handle the infeasibility of generated solutions to find a collision-free optimal path for a robot.

In this paper, we formulate the problem of path planning for a robot, creating zones which are neighbors to the corners of the static obstacles in an environment. This helps to reduce the search space to design a path. Our formulation is based on the technique to derive an optimal path, ensuring that a robot travels from its initial point to a destination point through these zones avoiding the collisions. Further, we modify the mutation operation to produce a solution by strictly substituting a different zone into the existing solution from the reduced search space. Thus, we proposed a

GA-based planning method and incorporated the modified mutation operation into it to tackle the premature convergence. For a fair comparison, we also implement two other widely studied nature-inspired algorithms for path planning problem, viz. Simulated Annealing (SA) [11] and Tabu Search (TS) [12] and integrate the modified mutation operation into their basic framework. Through extensive simulations, we show that all the three approaches are able to generate feasible solutions, but the proposed GA-based solution method produces better results with good convergence compared to SA and TS.

Further, the paper is organized into several sections: Sect. 2 describes the problem formulation along with the environment representation. Section 3 explains the design and implementation of evolutionary algorithms for the addressed problem. Section 4 provides the experimental results and comparative analysis. Finally, Sect. 5 concludes the study done in this paper and provides future directions.

2 Problem Formulation

In this section, we describe the real-space representation as an environment which comprises the free space and the obstacles. A suitable environment representation is required to find a feasible path for a robot to reach its destination. Several path planning methods use the grid-based model [4] where the real-space is divided into grids. Such a layout can be characterized as a two-dimensional (2D) coordinate plane which allows straightforward calculation of the distance between points connecting two grids. Therefore, we have adapted this model as it can simulate real-world scenarios and are easy to understand. Here, we formally define the mathematical framework where the robot has the knowledge about the environment. In the grid-based model, the whole space is divided into t number of grids which can be expressed as

$$G = \{g_i | \forall 0 \leq i \leq t - 1\} \tag{1}$$

where g_i is the grid identifier. The grids occupied by the obstacle can be denoted as O, where O is the subset of G. Therefore, the obstacle-free grids $F = G - O$ from which Z zones are identified to find the feasible path without any obstacles. This finally reduces the search space.

An example is shown in Fig. 1 which illustrates the grid model used for our study. Here, the environment is divided into 10×10 grids. Therefore, the environment consists of 100 grids in total. Each grid is having a length and breadth of 1 unit. The grids in black color are the static obstacles, and the rest of the grids are free grids where a robot is free to move. From the set of free grids, we create different subsets of colored zones which are neighbor grids of the obstacles' corner as shown in Fig. 2. Altogether we identified 12 zones which consist of 36 colored grids, i.e., 36% of the G and 56% of F. This results into reduced search space and less computation time to generate a feasible and optimized path. For a robot where there are obstacles between

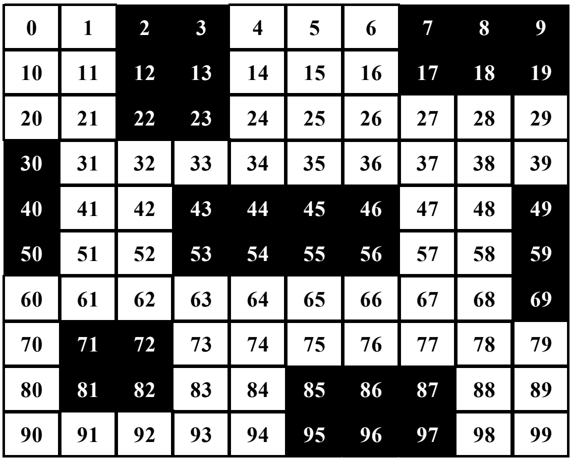


Fig. 1 Example 10 × 10 grid-based environment

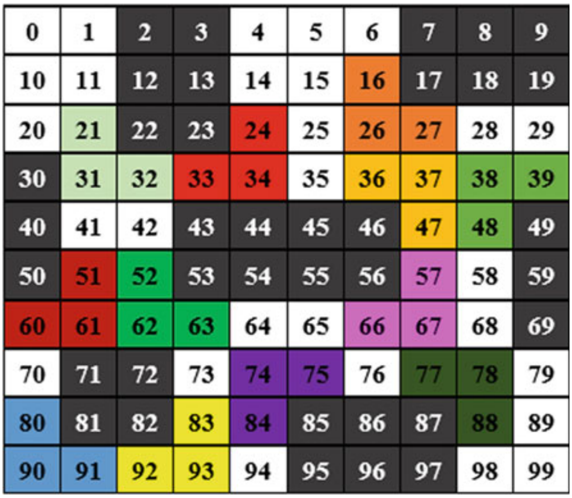


Fig. 2 Example 10 × 10 grid-based environment with zones

the start position and the goal position, the path is the one closer to the corners of the obstacle.

Further, we have adapted the coordinate system model for the environment which enables to calculate the Euclidian distance and check the feasibility of the path easily. For the grid environment in Fig. 2, the top left corner of the grid g_0 is the origin. We assume the robot travels through the midpoint of each grid. The coordinates of g_0 are (0.5, 0.5), g_1 are (1.5, 0.5), g_2 are (2.5, 0.5), and so on. Assuming g_0 (0.5, 0.5) is the starting point for the robot and the destination is g_{99} (9.5, 9.5). The X and Y coordinates of a grid can be calculated as follows:

$$X_i = \text{modulus}(g_i, 10) + 0.5 \tag{2}$$

$$Y_i = \text{floor}(g_i/10) + 0.5$$
$$0 \le i \le t - 1 \quad (3)$$

For a mobile robot, we need to find the shortest path between its starting and destination point. Therefore, the optimization problem becomes the minimization of distance to be travelled by the robot avoiding the obstacles. There is a possibility that paths generated may have obstacles. In order to compute the distance of these infeasible paths, we impose a penalty based on the number of obstacles on those paths. As a result, these paths will have a larger distance. The distance function [4] can be formulated as

$$D = \begin{cases} \sum_{b=1}^{n-1} \text{distance}(g_b, g_{b+1}) & \text{for feasible paths} \\ \sum_{b=1}^{n-1} \text{distance}(g_b, g_{b+1}) + \text{penalty} & \text{for infeasible paths} \end{cases} \quad (4)$$

where a and b are the two consecutive grids in the path and

$$\text{distance}(g_b, g_{b+1}) = \sqrt{(x_b - x_{b+1})^2 + (y_b - y_{b+1})^2} \quad (5)$$

Hence, the objective function can be characterized as:

$$\text{Min}\{D\} \quad (6)$$

where D is the total sum of the distance between all connecting grids of the path. Coordinates of the obstacles are used to generate equations of their edges which help in checking the feasibility of the path. The determinant is calculated between the equation of the line joining the grids and the equation of the edges of obstacles. The obtained determinant value concludes if there is any intersection between these lines. This helps to determine the feasibility of the path [13, 14].

3 Solution Techniques

We have implemented our solution techniques using three widely studied nature-inspired approaches, namely GA [4, 15, 16, 17], SA [11, 18] and TS [12, 19] for a fair comparison. The standard framework of each algorithm is used for the experiments. Further, we have integrated a modified mutation operation into each of these algorithms to generate a new potential solution. The pseudocodes for working of GA, SA, and TS developed for the proposed problem model are mentioned in Algorithm 1, Algorithm 2, and Algorithm 3, respectively. Now, we discuss the basic components of the algorithms.

Algorithm 1: The framework of GA

Input: $G, O, Z,$ population size, maximum iterations

Step1: **Population Initialization**: initialize a set of individuals of fixed length
Step 2: ***while*** termination criterion is not met ***do***
i. **Fitness evaluation** of the individuals using the objective function.
ii. **Selection**: the binary tournament selection is used
iii. **Crossover**: PMX technique is used for crossover
iv. **Modified_mutation**: see Algorithm 4
v. Fitness is calculated for the newly generated population
end while
Output: the feasible path

Algorithm 2: The framework for SA

Input: $G, O, Z,$ initial temperature, population size, maximum iterations

Step 1: **Population Initialization:** Randomly initialize a set of individuals of fixed length
Step 2: **Fitness evaluation** of the individuals
Step 3: **Best solution:** Select the individual with the best fitness
Step 4: Set Temperature to the initial temperature
Step 5***: while*** termination criterion is not met ***do***
i. **Create neighbour**: Modified mutation is used to create the neighbour
ii. Evaluate the fitness of generated individuals
iii. Sort population
iv. **Best solution**: Select the individual with the best fitness
v. update the temperature
end while
output: feasible path

Algorithm 3: The framework for TS

Input: $G, O, Z,$ initial temperature, population size, maximum iterations

Step 1: **Seed generation:** randomly generate an individual of a fixed length and store it as the best solution
Step 2: ***while*** termination criterion is not met ***do***
i. Generate neighbours to the existing individual
ii. Evaluate the fitness of all individuals
iii. Update the tabu list
iv. Select the best individual among all
end while
output: feasible path

0	31	62	66	99

Fig. 3 Encoding of an individual

3.1 Encoding of an Individual

All of the above three algorithms considered for our experiment begin with the encoding of an individual. An individual is a candidate solution for the path planning problem. Non-negative integers are used for the encoding of an individual as it takes less memory and less space in optimization than the other encoding techniques [10]. A fixed length of the individual is generated which comprises the grid labels to represent the path to be travelled by the mobile robot. The elements of an individual consist of a grid from where the path begins, the grids from the zones and the destination grid where the path ends. For example, Fig. 3 demonstrates an individual (for the 10×10 grid of Fig. 1) where the path begins at g_0 and g_{31}, g_{62}, g_{63} are zones through which the path is traced, and g_{99} is the end point of path. Here, the position of g_0 and g_{99} is fixed at the beginning and end of individual, respectively.

As GA and SA are population-based technique, we generate a fixed size of the initial population of individuals for the experiments. The pool of individual represents a variety of solutions. The generated population may contain both feasible and infeasible paths.

3.2 Fitness Evaluation

We evaluate the fitness of each individual using the objective function defined in Eq. 6 for all three algorithms. We calculate the fitness value as the total distance for feasible paths, and for infeasible paths, we take summation of total distance with penalty, respectively. The penalty must be greater than the maximum possible distance. Therefore, for our experiments, we took a penalty of 100 units. If there is an infeasible path between any two elements of an individual, we add 100 every time.

3.3 Selection for GA

We have used the binary tournament selection method which selects the best candidate solutions and passes them to the next phase of GA. The idea is to select a better individual and transfer them to the next generations [20].

3.4 Crossover for GA

The crossover operator is only employed for GA to recombine two selected individuals to create new solutions. For permutation encoding, partially mapped crossover (PMX) is widely used as it generates an individual without any repetition. This technique helps the robot not to travel through an already travelled grid again. In PMX, two crossover points are selected randomly, and respective elements are exchanged in such a way that there are no repeated elements in the individual [20].

3.5 Modified Mutation for GA and SA

To generate a new solution, we have developed a modified variant of single-point mutation [15] to ensure that a new grid is chosen specifically from the list of available zones Z. Algorithm 4 provides the steps followed for modified mutation for our experiments. An individual is selected randomly from the population. Also, a mutation point is chosen randomly. Then, a grid of the individual is replaced with a new grid from the zones without any repetition. This is employed to GA and SA only during our experiments. This operation helps to avoid premature convergence and increase the diversity of the population.

Algorithm 4: $modified\_mutation\ (individual, Z)$

begin
  Select an individual I randomly
  A $mutation_{point}$ is chosen randomly from I
  Select a new grid g_k from $Z - I$ randomly
  Replace the value at $mutation_{point}$ with g_k
end

4 Experiments and Results

This section describes the experimental setup and analyzes the results obtained. We have used two different sized datasets for our experiments, one with 10×10 grids (see Fig. 2) and other with 20×20 grids (see Fig. 4). We have implemented GA, SA, and TS as a solution technique to solve the proposed model. We take a population size of 10 for both GA and SA to experiment with the datasets. For GA, we use tournament selection with tournament size 2 and set the probability of crossover to 0.5. Mutation plays a vital role in generating better solutions and helps to escape out of local minima. Therefore, we set the probability of mutation in GA and mutation rate in SA to 0.8. Further, for SA, we set the values of a number of sub-iterations,

Fig. 4 20 × 20 grid-based environment

number of neighbors, initial temperature, and temperature reduction rate to 5, 3, 0.1, and 0.99. We keep the standard parameter settings for TS [12, 19]. The termination criterion for all three algorithms is kept as 100 maximum iterations.

We have conducted 50 independent runs of each algorithm using both datasets. We recorded the objective values of the best individual found at each generation. We also note the running time taken by each algorithm to its complete execution. In order to evaluate the efficiency of algorithms in terms of solutions generated, we have calculated the variance over the obtained results. For comparative study, the average values of 50 runs of each algorithm are summarized in Table 1 for 10 × 10 and 20 × 20 datasets. We can witness that all the three algorithms have been able to generate feasible and varied solutions. It can be observed that the GA-based solution approach has produced much better results compared to SA and TS. Figures 5 and 6 present the graph plot of average fitness versus iteration for 10 × 10 and 20 × 20

Table 1 Comparative results for 10 × 10 and 20 × 20 grids

10 × 10				20 × 20		
Algorithms	Best fitness	Variance	Running time	Best fitness	Variance	Running time
GA	14.204	0.0249	2.2555	29.451	0.0183	5.1117
SA	14.724	0.1703	6.2706	29.883	0.1141	15.8222
TS	15.68	3.5309	0.3612	30.682	0.5838	1.2295

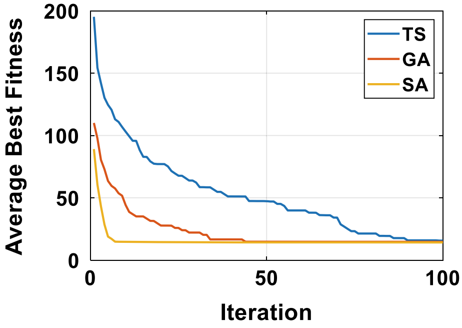


Fig. 5 Average best fitness over varying iterations for 10 × 10

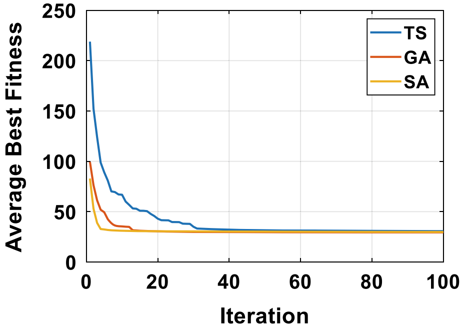


Fig. 6 Average best fitness over varying iterations for 20 × 20

datasets, respectively. The convergence of GA is much better and faster compared to SA and TS. Thus, we can conclude that GA has outperformed SA and TS in terms of solution generations.

To evaluate the significant difference, we have also conducted an ANOVA test with a confidence level of 95% using the best fitness values obtained at the last generation of each 50 runs of the algorithms. The graphs for comparison of significance difference of means for 10 × 10 and 20 × 20 are represented in Figs. 7 and 8, respectively. Here, GA, SA, and TS are represented by 1, 2, and 3, respectively, on Y-axis of the graphs. From Fig. 7, we can see that there is no significance difference in the means

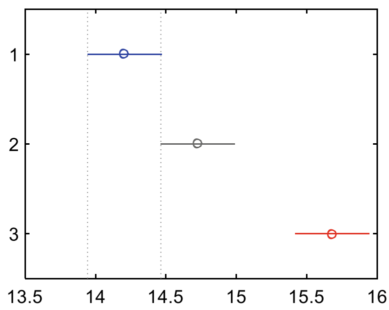


Fig. 7 Comparative results of ANOVA test for 10 × 10 using GA, SA, and TS

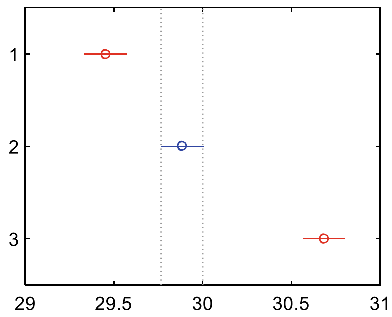
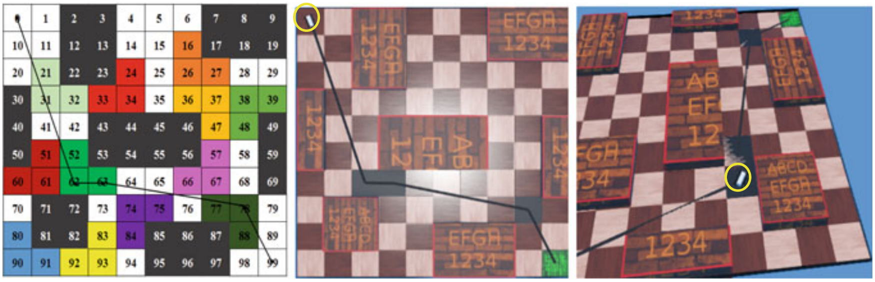


Fig. 8 Comparative results of ANOVA test for 20 × 20 using GA, SA, and TS



(a) Graphical illustration (b) Start of simulation (c) Instance during simulation

Fig. 9 Generated solution for 10 × 10 grid environment simulated on Webots for GA

of GA and SA. On the other hand, mean of TS is significantly different and larger than the means of GA and SA. From the analytical study of Fig. 8, we can conclude that the means of all three algorithms are significantly different. Here, again TS has produced a solution with larger variation and poor fitness values compared to GA and SA. For both of the datasets, GA has been able to generate a better solution with good convergence. We further simulated both the environments in Figs. 2 and 4 on Webots R2019a version 2.0 simulator for a six-wheeled robot. In Fig. 9, the leftmost image illustrates a feasible path generated by GA, and the two screenshots on the right demonstrate the simulation of the obtained path for 10 × 10 grid environment. The video of this simulation can be seen at the link provided in [21]. Here, the brown boxes with alphanumeric characters are obstacles, black grids are the zones given by GA, and green grid is the target position.

5 Conclusion

In this study, we have proposed a technique to design the path between grids for a robot using the zones. This helps to reduce the search space and find an optimal path for a robot, avoiding the collisions with the static obstacles. In order to increase diversity, we have incorporated a modified mutation technique to ensure a selection of grids from the available zones without any repetition. For a fair comparison, we have implemented three different solution techniques using GA, SA, and TS and check the efficiency considering two differently sized datasets. The comparative analysis and significance test of the algorithms are done using the results obtained. All three algorithms have been able to generate feasible solutions, but the GA-based technique has shown better performance in terms of solution generations. We have also performed the simulation of solutions obtained in Webots simulator using a mobile robot. Further, we will design an environment for a manufacturing process using multiple mobile robots and identify other critical objectives of the problem. We will also formulate the multi-objective path planning problem and solve it with other multi-objective EAs.

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Workspace Reconstruction for Designing Modular Reconfigurable Manipulators

Athul Thaliyachira Reji, Anubhav Dogra, and Ekta Singla

Abstract The world is getting primed for Industry 4.0. In this context, we propose a framework for the automatic reconstruction of workspaces where a manipulator is required to function. The manipulator can be customized using modular and reconfigurable approach with respect to the reconstructed workspace and the set of Task-Space-Locations (TSLs) and Base-Location (BL) specified. Focus is also laid on reducing the size of the workspace model while preserving its geometric features. In essence, our work aims to reduce human intervention in designing manipulators. The framework is developed in Robotic Operating System (ROS). The framework utilizes a depth sensor for generating data from the environment, which undergoes further processing to generate a mesh which represents the workspace. The framework is tested for different workspaces, and the results obtained are discussed.

Keywords Modular · Reconfigurable · Smart maintenance · Industry 4.0 · Robot Operating System (ROS)

1 Introduction

Trending industrial era is about smart and flexible productions, processes and interconnection of man, machines, software, devices, etc. Each of these are working together in a single environment leading to the rapid, economic and reliable production system. Industries evolved since the very first-time mechanization (first industrial revolution) came into picture, through the use of electrical energy (second industrial revolution) toward the time of automated production systems (third industrial revolution) [15], and new era of industry 4.0. Industry 4.0 is constituted by the Internet of Things (IoT), robots, flexible manufacturing systems, smart manufacturing technologies, smart maintenance, virtual and augmented reality, big data analysis, etc. Compared with today's factories, new factories employ a completely new approach

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A. Chakrabarti and M. Arora (eds.), *Industry 4.0 and Advanced Manufacturing*, Lecture Notes in Mechanical Engineering,
https://doi.org/10.1007/978-981-15-5689-0_24

to production and transform into complex and digitized production facilities. Our emphasis in this work is on flexibility. Reconfigurable manufacturing systems (RMS) are being developed to address the problems of fluctuations in customer demands as well as market turbulence [3, 13]. RMS is designed for rapid change in its hardware and software components. The main goal of RMS is to quickly change the production system making them highly customized and flexible. Modularity, integrability, scalability, flexibility, convertibility and diagnosability are the main characteristics of a reconfigurable manufacturing system [4]. In contrast to manufacturing cells or machine tools, robots are expected to be reconfigurable and becoming adaptable to the flexibility and performing a wide variety of tasks. The conventional robotic arms are designed individually and are having fixed configuration and workspace limits. Here, the term *configuration* refers to the manipulator's specification in terms of the number of degree of freedom (DoF), types of joints and connectivity angles between the links. The configuration of a manipulator affects its workspace structure, areas of application, payload capacity, etc. For *non-repetitive* tasks, where the required attributes of a robotic arm could vary, fixed configuration robots cannot stand. In such scenarios, variable or reconfigurable robots are needed. Reconfigurable manipulators are those which can adapt to any configuration and workspace as per requirement. Many researchers are actively involved in contributing to this field. The idea of reconfiguring a robot varies as some researchers are providing reconfigurability by locking and unlocking joints of manipulators [1, 10, 16] and others are using the modular approach [5, 7, 16, 17]. In the modular approach, modules are designed as link modules, joint modules and end-effector modules. These modules can be assembled in different ways to get a required configuration of the manipulator.

Non-repetitive tasks generally include maintenance tasks. These are the tasks which are used to restore and prevent malfunctioning. Maintenance is categorized into preventive maintenance, scheduled maintenance and unforeseen maintenance [18, 21]. Robots for maintenance tasks can be found in many applications, viz. nuclear industries, highway maintenance, railways, power line maintenance, aircraft servicing, etc. [18]. Sometimes, due to very complicated maintenance tasks (welding in a cluttered environment), fixed robot configuration may not suffice. Therefore, the aspect of customization is introduced. However, specially designed manipulators are not economical and feasible every time, and thus, reconfigurable manipulators fit better. For a given task-space-locations and a base point, a robotic arm can be configured using a set of three modules named as Heavy (H), Medium (M), Light (L) as shown in Fig. 1. Modules can be assembled in series according to assembly rules defined in [20], and required manipulator configuration can be developed. Increased automation, flexibility, smart manufacturing, smart maintenance and reconfigurable systems result in time and cost-efficient production system. Our objective is to design a manipulator which can operate in the given workspace using a set of modules. Depending on the workspace and the TSLs, the configuration of the modular manipulator would be different. However, the workspace will remain the same with respect to time apart from the manipulations the manipulator does. Therefore, there is a need to define the workspace and the TSLs in an efficiently and effectively. We cannot specify the entire workspace by making real-world measurements since it could be

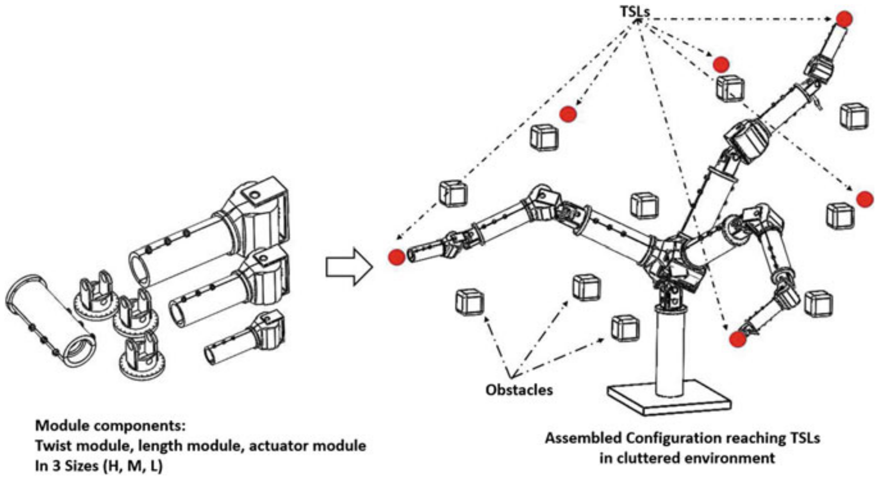

Fig. 1 Modular reconfigurable serial manipulator

out of scale. It might not take into consideration all the obstacles and can consume a lot of time and resource. These challenges will become tougher as the environment gets more complex. It is also not very efficient to prepare a CAD model every time as the workspace undergoes changes. Hence, we have chosen the method of reverse engineering the workspace using surface reconstruction.

This paper is organized as follows: Sect. 2 contains the problem definition, Sect. 3 briefs about the different environmental hierarchies, Sect. 4 lays down the methodology to reconstruct the environment followed by the results obtained in Sect. 3 and conclusion in Sect. 4.

2 Problem Definition

In this work, we are presenting a framework to address the following problems:

- Automating the modeling of workspace.
- Reducing the size of the workspace model while preserving its geometric features.
- Minimizing human intervention.

An attempt is made to provide this framework through the utilization of depth sensors (RGB-D cameras). The depth cameras in the current market possess high frame rates for 3D data acquisition (*Kinect v2* has a maximum frame rate of about 30 Hz [12]). Cost of depth cameras are significantly less compared to laser scanners and can give a real-time performance with low computational costs and time. The data capturing part of our framework is conceptually similar to the *KinectFusion*

[9]. The reason we are not using it in our framework is because of its proprietary nature, hence failing to carry out customizations from our end. The workspace is then reconstructed by applying surface reconstruction algorithms on the point cloud data captured.

3 Environment Hierarchies

The environment where the manipulator has to work can be seen in different layers of hierarchy. It can be divided into two levels as upper and lower as shown in Fig. 2. The upper layer includes environments involving several fields of application of manipulators, such as industrial manufacturing shops, assembly shop, maintenance- repair, services (pick and place), medical surgery, reconfigurable manufacturing cells and so forth. The lower layer consists of the environments with a single field of application. For example, an assembly application would consist of tasks like pick and place operation, object alignment and orienting in the assembly operation; maintenance task would include welding, cleaning, painting, visual inspection, or temporary manufacturing task. Thus, for each layer and its components, an environment changes and this change is to be addressed in an effectively. In each environment, the location of task spaces is identified where the end effector should reach and work effectively. The base location can be chosen arbitrarily, and accordingly, the optimal manipulator configuration is synthesized as explained in [20].

For every lower layer of environment hierarchy, accordingly, different designs of modules would be required. Module design will vary with the application. The modules will differ in sizes, joint type, actuator size, end-effector type and so forth. This gives an idea of developing modular libraries containing all kind of variations to span the modular reconfigurability on a large scale.

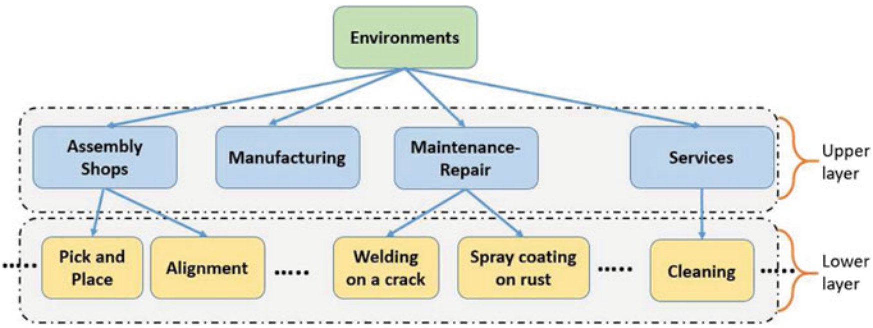

Fig. 2 Environment hierarchy

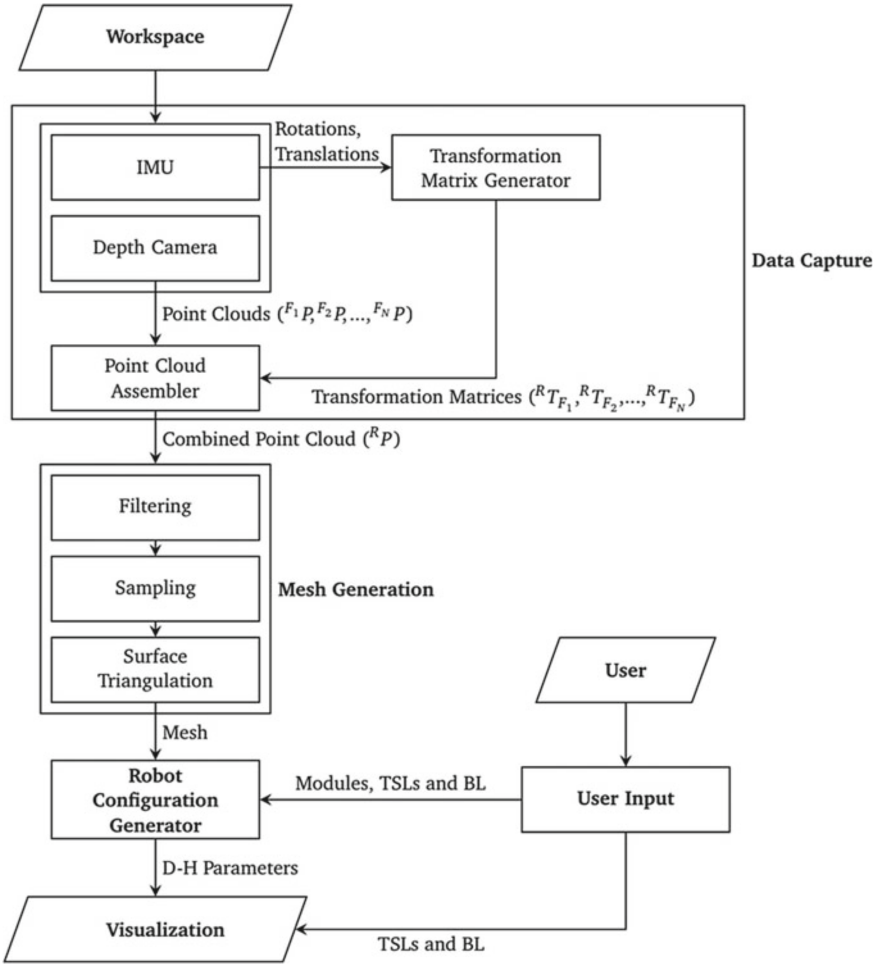

Fig. 3 Flowchart of the proposed framework

4 Workspace Reconstruction Framework

The proposed framework is generic in the sense that it will be operational for any depth sensor, workspace, choice of modules and choice of BL and TSLs. The framework is broadly divided into five parts: data capture, mesh generation, visualization, user input and robot configuration generation. The framework is being developed in Robot Operating System (ROS) and is depicted in Fig. 3.

4.1 Data Capture

The raw point clouds are captured from the workspace from different orientations and assembled into a single point cloud with respect to a single standard frame. This phase consists of the following steps:

Workspace Capture: The depth camera takes several three-dimensional depth images of the workspace, and these are recorded in the form of point clouds. This makes available the information regarding the workspace to the framework. The distribution of the point clouds in the image represents the geometry and the clutter of the workspace. The depth camera has to capture multiple images from different orientations for the following reasons:

- The entire workspace may be too big to be recorded in a single image.
- The workspace may contain objects which we may need to record completely. Therefore, several depth images of the object have to be taken from different angles.
- If more exact representation is required, several depth images will have to be taken with a slight change of orientation so that a denser point cloud will be obtained.

The inertial measurement unit (IMU) attached to the depth camera is used in determining the change in orientation and position of the depth camera as it moves and captures multiple images. Most of the depth sensors available in the market (e.g., Microsoft Kinect, Intel RealSense) consists of a built-in IMU to keep track of its orientations. They generate point clouds in different frames since the camera moves as it captures data. The point clouds captured can be represented mathematically as:

$$^{F_1}P, {}^{F_2}P, \ldots, {}^{F_n}P \tag{1}$$

where ^{F_n}P is a point cloud which is a set of three-dimensional coordinate points with respect to F_n and F_n is the frame with respect to which the point cloud is recorded.

Transformation Matrix Generator: The output from the IMU is used by the transformation matrix generator to make transformation matrices with respect to a standard (world/base) frame. Each generated transformation matrix is time stamped. The output can be represented simply as the transformation matrices from point cloud frames F_n to the standard frame R:

$$^{R}T_{F_1}, {}^{R}T_{F_2}, \ldots, {}^{R}T_{F_n} \tag{2}$$

Point Cloud Assembler: It assembles the recorded individual point clouds in different frames together to form a single point cloud with respect to a standard frame. Each point inside the point cloud are multiplied with their corresponding transformation matrix to get the point clouds with respect to a standard frame:

$$^{R}p = {}^{R}T_{F_n}{}^{F_n}p \quad \text{where} \quad {}^{F_n}p \in {}^{F_n}P \ , \ {}^{R}p \in {}^{R}P \ , \ n \in \left\{1, 2, \ldots, N\right\} \tag{3}$$

p is a point belonging to the point cloud P obtained when the depth sensor was at an orientation F_n, and R is the standard frame to which all point clouds are being transformed to. The correspondence between the point cloud and its respective transformation matrix is established by comparing their time stamps. These point clouds after transformation are then stacked or assembled to form a single point cloud. The output from the data capture module will be a single point cloud containing all the data points scanned from the workspace. The resulting point cloud is recorded in point cloud data (PCD) format.

4.2 Mesh Generation

This is the second phase of the framework as shown in Fig. 3. It takes as input the resulting single point cloud with respect to a standard frame from *Data Capture* phase and gives a mesh as its output. This phase further breaks down into the following steps:

Filtering: The point clouds obtained from depth cameras like Kinect can contain artifacts like noises and outliers due to the inherent noises generated by the sensor or due to the lighting condition of the workspace [2]. They can disturb the optimization process later on in the framework resulting in suboptimal configurations. Hence, these artifacts have to be removed while preserving the features of the point cloud. Based on [8], we have currently used *Voxel Grid (VG) filter* due to its markedly low computational costs compared to the rest. It was implemented using the *Point Cloud Library (PCL)*[19]. The *VG algorithm* works by creating a voxel grid over the point clouds and then approximating all the point clouds inside each voxel to a single point. The approximated point will be the centroid of the points present in the voxel.

Downsampling: *Downsampling* is the process by which the number of points in the point cloud is decreased while its ability to represent the object or workspace in our case remains intact. The raw point clouds are excessively dense which is good for many applications but that is not the case here. It can slow down the optimization process drastically without any benefit. The *VG filter* causes downsampling as it performs filtering since all the point clouds present in a voxel are reduced to one. Too much of downsampling will result in a point cloud which is sparse, and it will lose all its workspace representation accuracy. Thus, a threshold has to be met on the downsampling process. The amount of downsampling done can be adjusted by changing the voxel size.

Surface Reconstruction: Surface reconstruction is the process by which an object is reconstructed using the data obtained by sampling the object. It is a field under development under the realm of computer vision and graphics. In our work, surface reconstruction is used to reconstruct the workspace for designing an optimal manipulator. It gives a reasonably accurate model of a cluttered environment which can be very tedious to model otherwise. Even though there are many widely used algorithms, constructing reliable and accurate models from point clouds remains an open problem. We have used the *Fast Surface Reconstruction Method* [14] for constructing meshes from point cloud data. It gives good performance even when the data is noisy and of varying density. It also gives near real-time performance. This step takes in the *PCD* file as the input and generates a *STL* file as the output. A mesh representation is necessary for running the optimization processes in the later part of the framework.

5 Results

A virtual workspace and a depth sensor are being used in this work for capturing the point cloud data. This virtual world was simulated in Gazebo (Version 9.0.0)[11]. This was necessary because of the following advantages it offered:

- For developing a robust framework, testing in a variety of different environments will be required. With time as a constraint simulating a wide range of workspaces would be better than setting them up in the real world. A virtual environment gives better control to adjust its complexity.
- By conducting a comparison between running the framework using the data generated by virtual and real workspaces, the effect of various noises and distortions can be studied.
- Different methods of holstering and moving the depth sensor can be carried out in a controlled manner in a virtual workspace to find out the most effective way.

The framework is being developed using *ROS Melodic Morenia* in an *Ubuntu 18.04 LTS* operating system. A model of a Kinect sensor was rigidly attached to a rotating platform. This system was then placed in a world in Gazebo. The movement of the system was accomplished using the *ros_control* [6] package. The platform was made to rotate at an angular velocity and frame update rate of the Kinect sensor for two different workspaces, see Figs. 4a and 5a. During the simulation, data in point cloud form was published by the sensor. This was then transformed using the transformation data received from using the movement commands directly and then assembled. Filtering, downsampling and surface triangulation were subsequently carried out to create the final mesh which was recorded as an STL file.

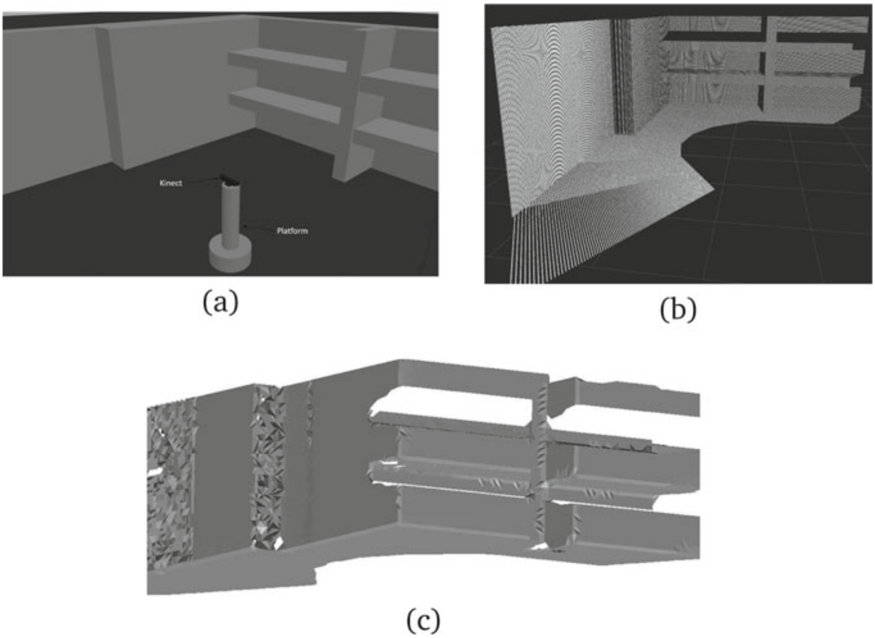

Fig. 4 Workspace-1 (**a**) Gazebo environment with kinect sensor, (**b**) point cloud captured, and (**c**) mesh generated

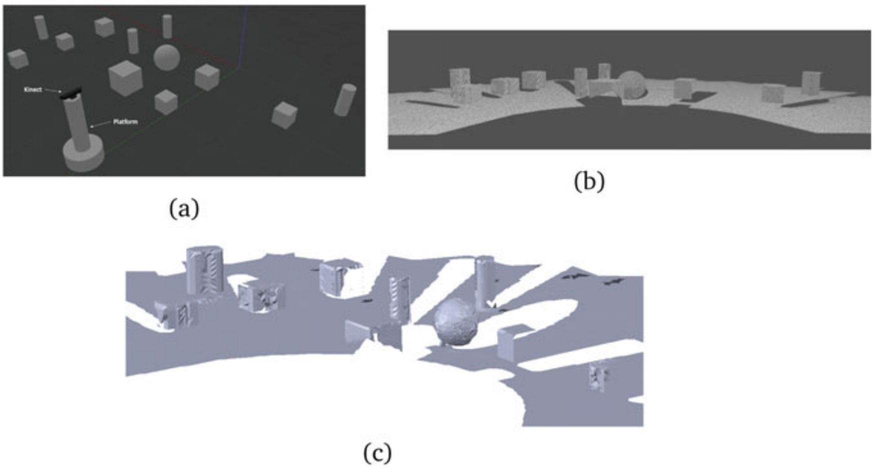

Fig. 5 Workspace-2 (**a**) Gazebo environment with kinect sensor, (**b**) point cloud captured, and (**c**) mesh generated

Table 1 Specification of the parameters and results obtained from the simulations

Workspace	Angular Velocity of the platform (°/s)	Frame update rate of kinect (Hz)	No. of points in the captured point cloud (file size)	No. of points after filtering and downsampling
1	20	2	3,750,000 (96.8 MB)	26,384
2	10	2	3,250,000 (59.6 MB)	17,052

Each depth image contains 2,50,000 data points. Fifteen depth images with respect to different frames were captured for workspace-1 and 13 for workspace-2 and were assembled using the framework as depicted in Fig. 3 to form a single point cloud with respect to a standard frame. When the angular speed was varied, keeping the frame update rate fixed at 2 Hz, it was observed that, at an angular speed of around 60°/s the images started to break, while decreasing the angular speed to around 1°/s caused the system to crash due to the large size of the points being generated. Filtering and downsampling brought down the number of point clouds significantly while preserving the geometric features of the workspace, values of which are described in Table 1. Triangulation of the resulting point clouds and corresponding mesh is shown in Figs. 4c and 5c. This framework is further to be used in the design of the modular reconfigurable manipulators, where the framework can check the change in the workspace and update the configuration of the manipulator accordingly in minimal time.

6 Conclusion

A framework for the automatic reconstruction of workspaces where a manipulator is required to function is presented. The framework was run for two different workspaces, and the results were presented. Challenges and limitations were identified by studying the effect of varying different parameters. We were able to generate a mesh file which represents the workspace with sufficient geometric features with minimal data.

Further development of this framework involves implementing and integrating the following phases—*Visualization*, *User Input* and *Robot Configuration Generator*. The framework will also be tested with a real depth sensor, and the results will be compared with that of the virtual environment.

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Machine Component Fault Classification Using Permutation Entropy and Complexity Representation of Vibration Signals

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Abstract In this work, we explored permutation entropy and complexity representation for classification of machine component fault signals. The proposed method is computationally inexpensive and has the ability to handle nonlinear and non-stationary signals. We used vibrations signals collected from normal and faulty ball bearings to demonstrate the effectiveness of the permutation entropy and complexity representation. We performed a sensitivity analysis to study the effect of representation parameters and signal length on the signal classification. We observed that embedding dimension $D = 3, 4, 5, 6$ and embedding delay $\tau = 1, 5$ are appropriate for good class separability in this application and the separability of classes improves with increasing signal length N. The overall accuracy of signal classification varies from 90 to 100% depending on signal length.

Keywords Fault classification · Permutation entropy · Complexity

1 Introduction

Industrial Internet of Things (IIoT), the implementation of IoT in manufacturing settings, has bridged the gap between operational technology and information technology. However, the massive volume of data is a challenge to designing real-time solutions for smart manufacturing. Most of the manufacturing applications are data-rich and knowledge-sparse [1]. They generate an enormous amount of data. The

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A. Chakrabarti and M. Arora (eds.), *Industry 4.0 and Advanced Manufacturing*, Lecture Notes in Mechanical Engineering,
https://doi.org/10.1007/978-981-15-5689-0_25

burden of transferring data to the remote cloud processing center puts a strain on transmission bandwidth and storage volume. Edge computing can alleviate the burden of high-volume data transmission. Edge computing devices such as smart gateways can enable decentralized data processing components at the network edge [2, 3]. The edge computing devices can store and process raw data to support cloud devices in releasing bandwidth pressure, reducing latency, and enhancing security and privacy. A combination of cloud and edge computing is the most promising solution for complex smart manufacturing systems [4].

Generally, manufacturing processes generate high dimensional multivariate data [5, 6]. Dimension reduction is a necessary step for machine learning algorithms to yield high performance. If dimension reduction and data reduction can be achieved in edge computing devices, knowledge-rich lean data can be transmitted to cloud for machine learning functions. In this paper, we present permutation entropy and complexity representation as a means to reduce a signal of finite length to a point in two-dimensional space. In other words, a signal of length n is reduced to a representation of two features.

Recent advances in using entropic measures for feature extraction from time series show a promise for edge computing applications when analysis of complex and nonlinear sensor signal is involved. Approximate Entropy (ApEn) [7–9] and Sample Entropy (SampEn) [10] were developed for characterizing nonlinear time series in biomedical applications. For PHM applications, ApEn [11, 12] was adopted for monitoring machine health and SampEn [13–15] for bearing fault diagnosis. Multi-scale entropy method developed by Costa et al. [16, 17] is used for machine health monitoring. Zhang et al. [18] applied multi-scale entropy method for bearing fault application. Permutation entropy introduced by Bandt and Pompe [19] has been used for analyzing and characterizing nonlinear time series. Studies have adopted permutation entropy for fault classification of mechanical components [20, 21]. Using permutation entropy alone as a feature limits its ability to differentiate different types of faults. Wu et al. [22] found that permutation entropy on its own as a feature does not fare well with classification algorithms.

In this work, we use permutation entropy in combination with complexity measures to overcome the shortfalls of using permutation entropy alone for component fault classification tasks.

2 Methods

Shannon entropy, $S[P]$, is designed to compute the information associated with a process described by a probability distribution $\{P = p_i : i = 1, 2, \ldots, M\}$. However, $S[P]$ becomes less effective in characterizing processes that exhibit organized patterns [23, 24]. In addition, Shannon entropy on its own does not capture temporal relationship, and poorly characterizes highly nonlinear processes (e.g., chaotic systems). To overcome the issues with Shannon entropy, Bandt and Pompe (BP) [19] formulated a method to extract the underlying probability distribution from time series. The BP method is non-parametric, rank based, and the probability of the ordinal patterns is invariant to nonlinear monotonic changes [24, 25]. In addition, the BP method is insensitive to nonlinear drifts and non-stationary signals [25–27]. For a given time series $\mathbf{x} = \{x_t : t = 1, 2, \ldots, N\}$, at each time instances, a sequence of values $\mathbf{x}_s = \left\{x_s, x_{s+\tau(1)}, \ldots, x_{s+\tau(D-1)}\right\}$ is selected, where D represents the embedding dimension and τ represents the embedding delay. The embedding dimension D reflects the amount of information captured in $\mathbf{x}_s$. An ordinal pattern $(0\ 1\ \ldots\ D-1)$ is assigned to $\mathbf{x}_s$ such that $(0\ 1\ \ldots\ D-1) \rightarrow \left\{x_s, x_{s+\tau(1)}, \ldots, x_{s+\tau(D-1)}\right\}$. The values of $\mathbf{x}_s$ are then sorted in ascending order at the same time and in the same order the corresponding ordinal pattern is shuffled. The shuffled ordinal pattern is denoted as π_i. When the embedded dimension is D, $D!$ permutation patterns are possible. Thus, $p_i = |\pi_i| / \sum_{i=1}^{D!} |\pi_i|$ for $i = 1, 2, \ldots, D!$ and $P = \{p_i : i = 1, 2, \ldots, D!\}$ is the probability distribution of the permutation patterns in the signal. The permutation entropy is computed as

$$S[P] = -\sum_{i=1}^{D!} p_i \log(p_i) \tag{1}$$

The normalized permutation entropy is given by

$$H_{\mathrm{S}} = \frac{S[P]}{\log D!} \tag{2}$$

where $H_{\mathrm{S}} \in (0, 1)$.

Entropic measures, like permutation entropy, are able to quantify information but they do not capture the structure or patterns in a process [28, 29]. Statistical Complexity Measures (SCM) were developed to identify the organizing patterns [24]. Jensen–Shannon complexity C_{JS} which combines both information and disequilibrium measures has demonstrated effective detection of the underlying dynamics. It is defined as [30, 31]

$$C_{\mathrm{JS}} = Q_{\mathrm{J}}[P, P_e] H_{\mathrm{S}} \tag{3}$$

where $P_e = \{1/D!, 1/D!, \ldots, 1/D!\}$ is the uniform distribution and disequilibrium $Q_{\mathrm{J}}[P, P_e]$ is Jensen–Shannon divergence that links two probability distributions, P and P_e:

$$Q_{\mathrm{J}}[P, P_e] = Q_0 J[P, P_e] \tag{4}$$

where

$$J[P, P_e] = S[(P + P_e)/2] - S[P]/2 - S[P_e]/2 \tag{5}$$

and Q_0 is a normalization constant equal to the inverse of the maximum possible value of $J[P, P_e]$, can take; it happens when one of the values of P is 1 and all other values are 0 [24]. The Q_0 is computed using the following equation [32]

$$Q_o = \frac{1}{-\left(\frac{1}{2}\right)\left[\frac{D!+1}{D!}\log(D!+1) - 2\log(2D!) + \log(D!)\right]} \quad (6)$$

The normalization term Q_0 ensures that $0 \leq Q_J[P, P_e] \leq 1$. The Jensen–Shannon divergence quantifies the difference between two probability distributions. It uses two different probability distributions P and P_e, where P is the probability distribution, which represents the state of the system being monitored and P_e is a uniform distribution, which serves as a reference [24].

3 Application: Ball Bearing Condition Monitoring

The permutation entropy and complexity representation described above can be used for fault classification of any rotary components of a machine. For demonstration purposes, we use two classes of vibration signal samples from ball bearing dataset provided by the MFPT Society [33]. Figure 1 shows the schematic of the methodology for bearing fault classification using the proposed permutation entropy and complexity signal representations.

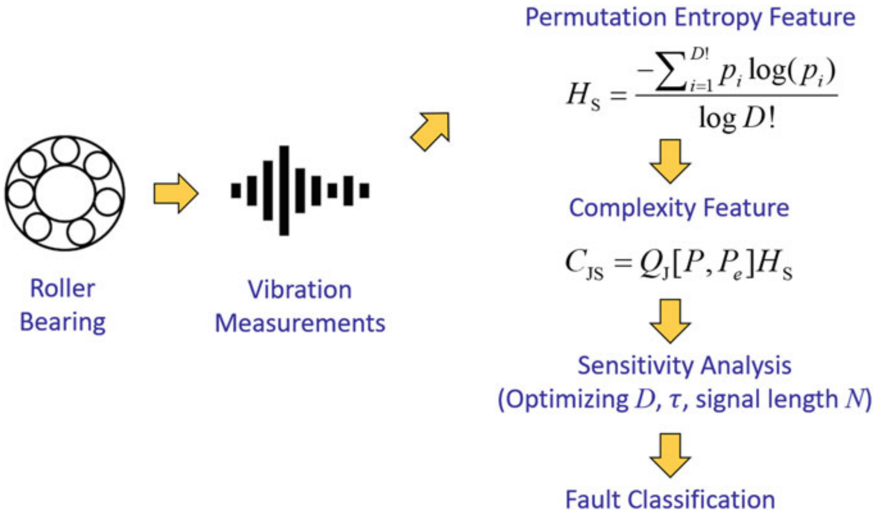

Fig. 1 Methodology for roller bearing fault classification using permutation entropy and complexity classification

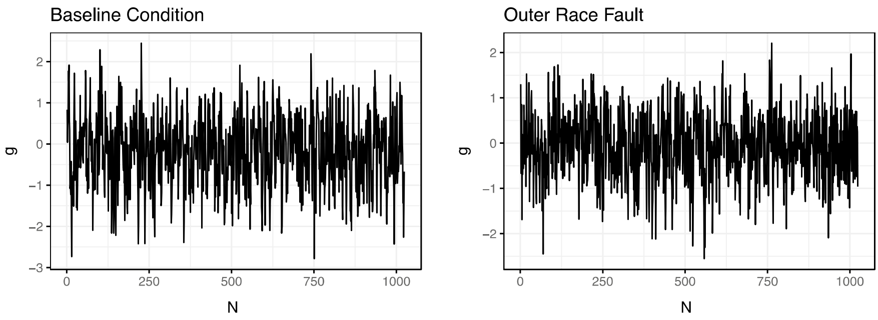

Fig. 2 Sample vibration signals. Left figure is a baseline condition signal. Right figure an outer race fault condition signal. Length of sample signal is 1024 data points. Sampling rate = 97,656 sps, load = 270 lb, and input shaft rotational speed = 1500 rpm

We use three signals for baseline condition (good condition) and three signals from the faulty outer race of the bearing. Both the baseline and outer race fault signals were sampled at the rate of 97,656 Hz for 6 s. The machine was operated at 270-lb load and 1500 rpm input shaft rotational speed. Figure 2 shows the sample vibration signals representing the baseline and outer race fault conditions from the MFPT dataset.

For each of the six signals mentioned above, we computed H_S and C_{JS} using Eqs. (2) and (3) respectively. We performed a sensitivity analysis to study the effect of signal representation parameters (embedding dimension D and embedding delay τ) and signal length n on the ability of permutation entropy to separate faulty bearings from normal bearings.

In the current sensitivity analysis the following different setting were considered: embedding dimension $D = 3, 4, 5, 6$, embedding delay $\tau = 1, 2, 3, 4, 5$, and signal length $N = 2048, 4096, 8192, 16384, 32768$. The setting choice for D and τ were informed by an earlier study by Yan et al. [20]. The signal length is varied such that $n \gg D!$ is maintained, which is a condition required for differentiating chaotic and stochastic processes [25, 34]. For practical purposes, Bandt and Pompe [19] recommended $3 \ll D \ll 7$ and $\tau = 1$.

Figure 3 shows the matrix of C_{JS} versus H_S plots for $D = 6$. We did not include images for $D = 3, 4, 5$ to conserve space. The focus of our study is on the separability of different signal classes with respect different model parameters and signal length. We observed that $D = 3, 4, 5, 6$ and $\tau = 1, 5$ are suitable for good fault classification results. We noticed that the baseline signals are characterized by relatively high values of H_S and C_{JS} compared to those of the outer race fault signals. This observation is consistent $D = 3, 4, 5, 6$ and $\tau = 1, 5$. A random signal has the highest H_S and the lowest C_{JS}. The outer race signals are mapped much closer to the random signals than the baseline signals. We also observe that with an increase in signal length, the separability, and hence the classification accuracy improves.

To verify the visual observation, we used Support Vector Machine (SVM) to classify signals and assess the classification accuracy. Table 1 summarizes the results

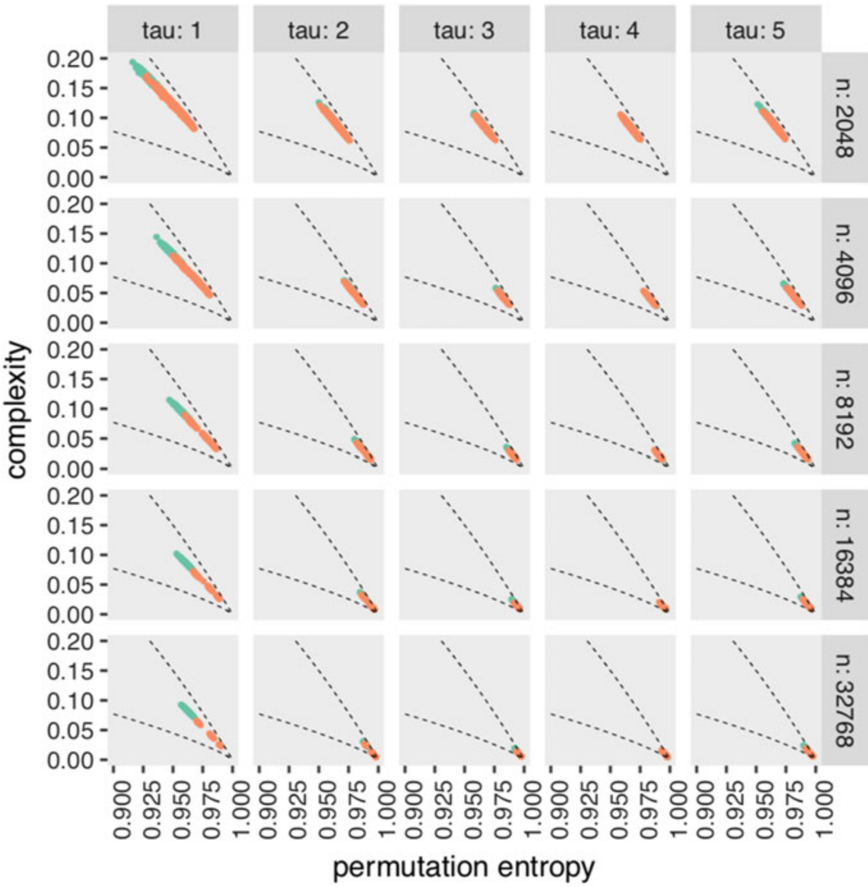

Fig. 3 H_S and C_{JS} values for $N = 2048, 4096, 8192, 16384, 32768$, $\tau = 1, 2, 3, 4, 5$, and $D = 6$. Load = 270 lb, Shaft Rate = 25 Hz. The dashed lines represent the lower and upper limit curves. Green color represents the baseline condition and orange color represents the outer race fault

Table 1 Accuracy and Area Under Curve (AUC) values for different signal lengths

Signal length	ACC (%)	AUC
2048	90.40	0.96
4096	93.70	0.99
8192	97	1
16,384	99.5	1
32,768	100	1

of SVM. We observed that the classification accuracy (ACC) and the area under curve (AUC) improves with increasing signal length as expect through visual observation of C_{JS} versus H_S plots.

4 Discussion

We observed that permutation entropy and complexity measures are suitable for bearing health condition states. The features C_{JS} and H_S together are able to differentiate between the normal and faulty health conditions of a roller bearing and the classification accuracy improves with an increase in signal length n. We observed that the choice of parameters embedding dimension and embedding delay is application-specific. For the ball bearing application discussed $D = 3, 4, 5, 6$ and $\tau = 1, 5$ are suitable for good fault classification performance. The proposed two-dimensional representation of sensor signals is able to generate linearly separable classes for the classification of different fault states for bearing with an accuracy of 90–100% as the signal length increases from low to high. The ability of features C_{JS} and H_S to handle nonlinear and no-stationary signals combined with inexpensive computation makes it suitable for classification using edge computing devices.

Though the permutation entropy and complexity representation is robust computationally and versatile for different types of signals, the optimal embedded dimension and embedded delay vary from application to application. They need to be determined empirically through sensitivity analysis. Since the accuracy of signal classification improves with signal length, this representation may not yield good results if the time series is short. These representation serve two important functions for practitioners. It can be used for both predictive analytics and visual monitoring of changes in mechanical component conditions. The two-dimensional map, C_{JS} versus H_S, can serve as a control chart or a dashboard showing the slow or sudden deterioration of the health condition of mechanical components.

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Sustainable Manufacturing

Barriers to Successful Implementation of Sustainable Practices in Small and Medium Enterprises (SMEs)

Sourojit Saha

Abstract SMEs are important players in the economic development of any country. The SMEs are found to be more efficient in providing more employment opportunities at relatively lower cost. The employment intensity of SMEs is estimated to be four times greater than that of large enterprises. Manufacturing firms consume a lot of resources, which raise serious concerns regarding sustainability of those resources. With increasing environmental concerns and globalization, SMEs now face the challenge of abandoning the traditional practices and adopting new sustainable practices. This paper tries to identify some of the barriers to successful implementation of these practices by SMEs.

Keywords Sustainable · Barriers · SMEs

1 Introduction

SMEs are important players in the economic development of any country. They provide more employment than any large firm. For example, in India, 63.3 million SMEs are generating 110.9 million jobs. Their contribution to the GDP is 28.77%. Of the 63.3 million SMEs, 19.6 million (31%) SMEs belong to the manufacturing sector which employs 36.0 million (32%) people [11]. Manufacturing firms consume lot of material resources and energy and are also a major polluter. With increasing environmental concerns, focus is now on achieving sustainability in this sector.

With increasing environmental concerns, people are shifting more towards adopting environmentally safe practices. Government and firms focus on attaining sustainability. Sustainable practices deal with economic, environmental and social sustainability. Environmental awareness is increasing among the common public. They now prefer to buy environment-friendly products. The firms that can quickly change their technology and products in accordance with changing customer preferences will survive in the long run. A firm needs to be financially strong and flexible so

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A. Chakrabarti and M. Arora (eds.), *Industry 4.0 and Advanced Manufacturing*, Lecture Notes in Mechanical Engineering,
https://doi.org/10.1007/978-981-15-5689-0_26

that it can readily change its technology, product, etc., with time and is not burdened by sudden changes in customer trends and government regulations. For these changes to take place, the workforce must be aware and ready to accept the new way of their working. The impact of a firm alone adopting the sustainable practices will be very less. In order to fulfil its goal, it must influence and encourage other firms (in supply chain) to adopt such practices.

A lot of research has been done on the field of sustainability, with each focusing on one definite parameter/factor that affects the sustainability of the firms. Almost all research adopts the survey as the method of data collection.

This paper tries to identify and present the parameters/factors, which affect the implementation of sustainable practices in firms, in a single paper. These 'parameters/factors' have been termed as 'barriers' in this paper for the ease of language and readability. Limitations and scope of future work have also been presented.

2 Literature Review

Often firms face problems while shifting from traditional practices to sustainable practices. Study of the literature reveals the problems faced by the firms in adopting sustainable practices. The factors identified are given in Table 1.

These factors may be divided into two broad categories of barriers:

i. Internal Barriers
ii. External Barriers

2.1 Internal Barriers

Internal barriers comprise the barriers that originate from within the organization. These include lack of resources (both financial and technological), lack of awareness among the managers and workers of the firm, the lack of commitment of the management and the tendency to resist the change in work habits. These internal barriers in turn influence the firm's policy and cause economic barriers. Adopting a greener operational practice will require the workforce to change their work habits.

Table 1 Identified factors/barriers

• Awareness of managers and workers and the pressure perceived by them • Size of firms • Technology • Consumer awareness • Financial resources	• Proper tools for evaluating the degree of implementation • Competition • Government regulations • Law enforcement • Collaboration among firms

Generally, the workforce resists such a change. Such a situation crops up when there is lack of awareness among the workers.

The various internal barriers are explained below.

Awareness of Managers and workers and the perceived pressure: In a study conducted on the level of pressure perceived by the managers of a firm and the awareness level of the managers, it is seen that firms with environmentally aware managers perceive the same pressure more intensely and take proactive measures. Also, it is seen that even though environmentally aware managers perceive a greater pressure, they respond to it with the same intensity as any other firms. That is, the response is dependent on the perceived pressure, whether the managers are aware or not is not of much significance [5]. The commitment of managers is also a barrier to the implementation of sustainable practices. Even though the managers may be aware, they may not be committed to its implementation. This is because of the economic barriers that they may face [10].

Size of firms: Adoption rate of sustainable practices is dependent on the firm size. Larger firms are in general targets of government regulation and public pressures. This is because they are perceived as more responsible and more powerful. On the contrary, small firms react to only direct pressures by the consumers [8]. Smaller firms perform better than larger firms. This is because they have a smaller consumer base and are hence more responsive to their demands. Being a small organization, they have the required number of employees and are hence more flexible in their functioning. Local firms also have a good network of their customers who would still be buying from them even if the prices increase slightly [1].

In a different study, it was found that firm size does not significantly affect the implementation of sustainable practices [7].

Majority of studies found some correlation between the firm size and sustainable practices. This field needs more attention.

Technology: Lack of technical knowledge is a major barrier to the successful implementation of sustainable practices. Firms in developing nations are forced to import sophisticated equipment from developed nations at a higher price. Lack of information sharing occurs due to confidentiality fears among companies. The government should improve the infrastructure and encourage research. The small firms can gain this technical knowledge with assistance from the government [8]. Technologies that reduce the resource consumptions such as shifting to alternate energy sources (solar, wind and biomass), choosing alternate manufacturing techniques, moving to computer-based modelling and testing rather than testing on physical prototypes and practices such as energy audits, application of 3Rs (Reduce, Reuse and Recycle) should be increasingly implemented in firms [14]. Implementation of newer technologies is costly and not available easily [10].

Proper tools for evaluating the degree of implementation: Firms may be eager to implement sustainable practices, but without proper evaluation of the degree of implementation, the objective is often lost. Such firms start with much enthusiasm, but as they do not get any reliable data, the motivation to continue dies. A proper evaluation scheme thus helps to fully implement the sustainable practices [4].

Financial Resources: SMEs are small organizations and are hence limited in terms of financial resources. They cannot dedicate their financial resources for changing their working habits. Often, shifting to sustainable practices requires sophisticated technologies, which are costly. Government policies should keep this in mind while deciding on policies [13].

2.2 External Barriers

External barriers are those that the firm has no control on and must change itself to fit in the world. External barriers include market competition, government regulations, technical information and external pressures. The market competition will include the customer pressures, market prices and peer pressure. As more and more people are getting aware of the environmental impact of manufacturing firms, they are starting to exert external pressures in various ways such as political activism and protests.

Various external barriers are explained below.

Competition: All firms are set up to make profit by selling their product and/or service, so whenever they face a competition, they take it up seriously and adopt a model that will improve their economic performance. With increasing globalization, local firms face more competition from international firms that adopt a more sustainable approach. Hence, the local firms are compelled to improve their performance. Hence, lack of competition acts as a barrier. Firms are more influenced by competition than by other factors such as regulations and consumer pressure. [15].

Consumer Awareness: All firms operate for the sole reason to sell their products to the consumers. So, consumers can exert their influence on the firms to implement better practices. Though consumers can influence the firms, there is a need for proper government regulations to encourage the firms to adopt better practices. This is because the consumers may not always be affected by the practices of the firm [12].

Govt. Regulations: The firms facing greater regulatory pressures tend to implement better practices faster [15]. Though consumer behaviour pressurizes the firms to adopt better practices, strict regulations must be in place to encourage firms to adopt them as the consumer may not be affected by the firms practices [2]. The government policies must encourage the firms to take up sustainable practices [8]. Lack of regulations and infrastructure by the government acts as barriers for firms to implement proper practices. Uncertainty about the future legislations also causes hindrance to it, as firms always tend to implement practices for the long term and do not want change the working habits [10]. However, government regulations and policies such as Waste Electrical and Electronic Equipment (WEEE) Directive and Restriction of Hazardous

Table 2 Various internal and external barriers

Internal barriers	External barriers
Awareness of managers and workers and the pressure perceived by them Size of firms Technology Proper tools for evaluating the degree of implementation Financial resources	Consumer awareness Competition Government regulations Law enforcement Collaboration among firms

Substances (RoHS) Directive have proven successful. These impose greater responsibility on the producers to manage the products and wastes they produce [12], forcing firms to adopt sustainable practices.

The influences of consumers are more profound than the influence exerted by the government. This is due to the fact that governments are more interested in observance of the rules and regulations [5].

Law Enforcement: Government regulations are useless unless they are enforced by the government. Lack and/or inefficient law enforcement is due to lack of infrastructure, lack of trained workforce, ineffective laws, corrupt officials and the cost of monitoring the progress [9].

Collaboration among firms: Collaboration is defined in [6] as 'a process through which parties who see different aspects of a problem can constructively explore their differences and search for solutions that go beyond their own limited vision of what is possible'. All firms have their fields of specialization. By collaborating and contributing to concurrent engineering for sustainable product development, the overall sustainability performance can be improved. Collaboration can also be fostered by implementing Green Supply Chain Management (GSCM) among various players of the supply chain, so as to reduce their overall environmental impact [3]. This increases the information sharing among the firms, which in turn improves the sustainability [4]. Also, collaboration among developed and developing nations, in the form of technology transfer (e.g. Make In India), must be encouraged so that sophisticated technologies are available at affordable prices [9].

Various internal and external barriers are shown in Table 2.

3 Framework and Methodology

SMEs are vital players in the economic development of any country. SMEs provide extensive employment and are hence a focus point of governments. Due to small size and workforce, they cannot dedicate much of their resources for implementing better sustainable practices. Various research papers have been published, addressing this issue. Most of the papers deal with only a few parameters. A proper identification

Table 3 Results of PESTEL analysis on various barriers/factors

Political factor	• Consumer awareness gives rise to political activism and protests
Economic factor	• Limited financial resources • Increased competition from international brands • High cost of implementation
Social factor	• Consumer awareness leading to change in consumer preferences • Aware managers perceive a greater pressure than others and act accordingly
Technological factor	• Lack of technical know-how • Unavailability of required technology • High cost of importing better technologies from foreign countries
Environmental factor	• Increase in pressure from government and consumers to implement environment-friendly practices
Legal factor	• Government making stricter rules • Uncertainty in future rules and regulations • Improve law enforcement

and understanding of these barriers are required before any further steps can be taken to implement sustainable practices among SMEs.

The research methodology consisted of study of the literature to identify the barriers and development of a survey questionnaire to collect data.

Ten barriers were identified in the first step. Keywords such as ‘Sustainable’, ‘SME’, ‘Barriers’, ‘Manufacturing’, etc., were used in Scopus and Google Scholar to find related papers. Thirty-three papers were selected for studying.

Questionnaires of various papers were studied, and then, suitable questions were framed according to the requirement of this survey. These papers are listed in the References and Bibliography section. Likert scale was used, with (1) meaning no impact, (2) for low impact, (3) for medium impact, (4) for high impact and (5) meaning very high impact.

Results of PESTEL analysis on various barriers/factors are shown in Table 3.

4 Discussion

After the study of the literature, barriers were identified and divided, depending on the degree of control of the firms over those barriers.

Internal barriers must be removed first, as these are under the control of the firm’s management. Among various internal barriers, management commitment must be addressed first. Management can, if they want, allocate funds for implementing sustainable practices and achieve the desired level of sustainability. Management will react positively if their managers are well aware of the implications of sustainable practices. Pressure perceived by the managers plays an important role in changing their stance on implementation. Smaller firms perform better in implementation of sustainable practices, because they have a smaller workforce and hence are more flexible. Larger firms with a large workforce and diverse consumer base find it more difficult and expensive to change their work habits. Most technological advances occur in developed countries. Unavailability of better equipment at a reasonable price in developing counties forces firms to buy them from developed countries at a higher price. The government should improve its infrastructure and encourage research & development. This will make better technologies easily available to smaller firms at an affordable price. As SMEs are limited in their resources, they cannot dedicate much of their resources to adopting different working practices. Government should give incentives and/or fund small firms for shifting to sustainable methods. Often the management is enthusiastic to implement sustainable practices, but it soon dies down. This is because they do not have any proper tool to measure the degree of implementation. As they do not see any significant changes visible to their eyes, the enthusiasm dies and they are back to working in their traditional way. Proper measuring tool must be in place to check the implementation. Proper guidelines must be made, preferably by government, to guide SMEs to implement sustainable practices.

External barriers force firms to change their practices in order to fit in the world. Most influential among the external barriers is the competition and consumer pressure. As consumers are becoming more aware of what product they are using and its environmental impact, their preferences are changing. Consumers now prefer to buy environment friendly products even if they are little expensive. With changing consumer preferences, the firms must change their working habits to continue in the business. With increasing globalization, international firms are now entering local markets. Local firms now compete with these large international companies, which already have in place proper environment-friendly processes. Local firms are now forced to adopt such practices to continue in the business. Many firms have a vision to expand to other countries. In order to set up their unit in other countries, they have to follow the guidelines of that country, which are often strict. Collaborations among firms must be encouraged as it increases information sharing. This way firms will come to know about different approaches to achieve sustainability. Government regulations often miss the mark that they intend to achieve. Lack of understanding of the existing laws and uncertainties in future legislations acts as barriers to implementation of sustainable practices. Firms are most interested in knowing the future legislations, so that they can plan accordingly for the long term. Inefficient law enforcement due to lack of infrastructure, lack of trained workforce, ineffective laws, corrupt officials and the cost of monitoring the progress gives firms an escape route from implementing sustainable practices. Law enforcement must be strengthened for proper implementation of government rules and regulations.

5 Conclusion

The purpose of this paper was to identify the barriers in implementation of sustainable practices in SMEs, which has been duly achieved. After the study, 10 barriers were identified and categorized into two categories, i.e. internal barriers and external barriers.

Inferences from the study show that:

1. Awareness among consumers, government and firm's managers is positively related to adoption of sustainable practices.
2. Consumer influence is more profound than government regulations.
3. Firms are more sensitive to competition than consumer pressure. Increased competitions increase the rate of adoption of sustainability practices among SMEs.
4. To achieve sustainability, mitigating internal barriers must be given higher priority.
5. Availability of affordable technology is a major issue. Government must improve its infrastructure and encourage research.

6 Limitations

Most of the researchers have used survey as the method of data collection. It is an easy and cost-effective method, and it has some limitations though. The limitations of such a method, as identified by the authors of their respective papers, are as follows:

1. Biased response in surveys
2. Limited sample size
3. Appropriate variables may not have been identified
4. Limited to small region
5. Specific to industry/region
6. Invalidated data.

7 Scope of Future Work

Scope of future work, as identified by the authors of their respective papers, can be stated as follows:

1. Improve the quality of data collected by:
   (a) Conducting the survey for a longer period of time
   (b) Using a larger sample size
   (c) Validating the data
2. Extend the survey to:
   (a) Different regions/countries
   (b) Different industries.

3. As surveys use human assessment, which are subjective in nature, to elicit information, one can come up with methods to actually monitor the CO2 emissions, waste disposal, etc.
4. Other variables may be adopted to assess the implementation of sustainable practices in firms.
5. Study the effect of firm size on implementation of sustainable practices, as there is no conclusive result on this.

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Synthesis and Testing of Novel Neem Oil-Based Cutting Fluid with Ionic Liquid Additives

Maddula Shanmuka Srinivas, R. Panneer, P. S. Suvin, and Satish V. Kailas

Abstract Mineral oils used in the industries as cutting fluids are discarded into the water bodies after use. They cause a lot of havoc to marine animals. Plant-based oils are searched as a replacement for the mineral oils. Ionic liquids are added as additives for better performance. In this work, oil in water emulsions is prepared with Neem oil as the base oil. Emulsifiers such as Tween 20 and Span 80 are used as surfactants. An ionic liquid named Trihexyltetradecyl Phosphonium Bis (2,4,4-trimethyl pentyl phosphinate) is added as an additive 2% (w/w). The prepared emulsions are tested as the cutting fluid during the drilling operation and compared with the cutting fluid available in the market. Results showed that the prepared emulsions are giving better performance in terms of axial force, torque, surface roughness. Thus, the prepared emulsions can be considered as one of the efficient alternatives for commercial cutting fluid.

Keywords Tool chip tribometer · Friction coefficient · Surface roughness · Ionic liquids

1 Introduction

Machining is one of the key operations to be performed for generating a product. Different machining operations such as turning, milling, etc., are performed to bring the raw material into the required size and shape. Drilling is one of the important machining processes for making the holes of the required size to join the materials. Drilling can be done in dry conditions without applying the cutting fluid. But the analyses have shown that the drilling process when carried out with the application

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A. Chakrabarti and M. Arora (eds.), *Industry 4.0 and Advanced Manufacturing*, Lecture Notes in Mechanical Engineering,
https://doi.org/10.1007/978-981-15-5689-0_27

of cutting fluid can yield in drilled holes of superior quality. A number of petroleum-based oils are used in the industry as the cutting fluids. But the problem with those cutting fluids is that they do not degrade into the earth and cause great havoc to the aquatic life when discarded directly into the water bodies. In this work, experiments are carried out on the based non-edible oils as an alternative to the petroleum-based oils. Plant-based oils have many superior qualities such as biodegradability, non-toxic, widely available. Neem oil is one which satisfies the above criteria. It is one of the widely available oils before being non-toxic and bio-degradable and environmentally friendly. One of the main issues with neem oil is its thermal stability. So, the ionic liquid is added as an additive to compensate for the thermal stability.

2 Literature Review

Kalhofer [1] showed that soluble oils cause respiratory and skin related problems. Dry machining is widely practiced in industries to avoid such problems. But the demand for achieving good surface quality, better machining efficiency, and higher speeds of machining paved a way for the search of cutting fluids which can optimize the above requirements. Vegetable oils are seen as a better alternative due to their low cost, safer for usage, less harmful for health and environment. Non-edible oils such as castor oil, neem oil, etc. are used to reduce the demand for vegetable oils. But low thermal stability is the main drawback with non-edible oils. To address this challenge, ionic liquids are used as additives. Ionic liquids are a class of novel solvents that have unique properties and promising applications in various diverse areas [2]. Zhou et al. [3] suggested that for actual industrial applications, addition of very low quantities of ionic liquids in lubricating oils leads reduction in friction and wear at both tribological evaluations at the laboratory scale and also full-sized dynamometer tests. An analysis of the cutting forces, thrust force, surface roughness by Goindi et al. [4] showed that addition of 1% concentration by weight of ionic liquid to the base fluid in Minimum Quantity Lubrication mode shows significant effect on the tribology of the machining process when compared to conventional flood cooled cutting, dry cutting, and machining with neat vegetable oil applied in MQL mode. Kamimura et al. [5] found that ionic liquids have superior tribological properties compared to conventional lubricants like synthetic esters, synthetic hydrocarbons, and fluorinated ethers. There is a considerable improvement of antiwear properties of ionic liquids by the addition of Tricresylphosphate (TCP) and dibenzyldisulfide (DBDS). Fraser et al. [6] pointed that phosphonium ionic liquids offer several advantages over other types of ILs, which includes higher thermal stability, lower viscosity, higher stability in strongly basic or strong reducing conditions. He also felt that an extensive amount of work has to be done their chemical and physical properties for a clear understanding of the structure-property relationship. Qu et al. [7] investigated the possibility of trihexyltetradecylphosphonium bis(2-ethylhexyl) phosphate as an antiwear lubricant additive. He found that this IL is completely miscible with different hydrocarbon oils. It also showed better corrosion resistance to cast iron at ambient environment and retained its thermal stability up to 347 °C with good wettability on solid surfaces. Another very unique property shown by this phosphonium-based ionic liquid is that when it is blended with lubricating oils, it has shown efficient antiwear and antiscuffing characteristics.

3 Materials and Methods

3.1 Base Oil–Neem Oil

Neem oil is selected as the base oil due to its eco-friendly nature.

3.2 Surfactants—Tween 20 and Span 80

Tween 20 and Span 80 are used as surfactants to mix the Neem oil with water. These are commercially used as food-grade emulsifiers. The chemical name of Tween 20 is Polyoxyethylene Sorbitan and that of Span 80 is Sorbitan Monooleate.

3.3 Selection of Ionic Liquid

The ionic liquid selected is Trihexyltetradecyl Phosphonium Bis (2,4,4-trimethyl pentyl phosphinate). It is a phosphonium based ionic liquid.

3.4 Preparation Method of Emulsions

The emulsions are prepared by mixing the base oil (Neem oil), water, emulsifiers (Span 80 and Tween 20), additives (Ionic liquid). The emulsions are prepared with mixing the base oil and emulsifiers with water in the ratio of 1:20. Two percentage of ionic liquid is added to the prepared mixture in the weight to weight ratio (%w/w) to form the emulsion.

4 Methodology

The work started with the preparation of cutting fluids for their optimal concentrations. The performance of the prepared emulsions is tested by performing the drilling

Fig. 1 Experimental setup used for drilling the holes with different cutting environments

experiments. The tribological performance is evaluated by carrying out by tool chip tribometer experiments. The obtained surface finish is tested using the 3D optical profilometer.

4.1 Machining Operation

Drilling is a machining process to evaluate the performance of the prepared emulsions. The reason for selecting the drilling operation is it is one of the widely used machining operations. A drill dynamometer is attached to the setup for measuring the Axial Force and Torque. The twist drill bit made of high-speed steel (HSS) is used as the tool. The workpiece is made of aluminium of grade T6061. A dynamometer (Kistler make) is used to find the Axial force (N) and Torque (N-m). All the experiments are conducted at the ambient conditions (Fig. 1).

4.2 Tool Chip Tribometer

It is one of the unique instruments used to find the frictional force and coefficient of friction acting on the nascent surface which is created immediately after the cutting

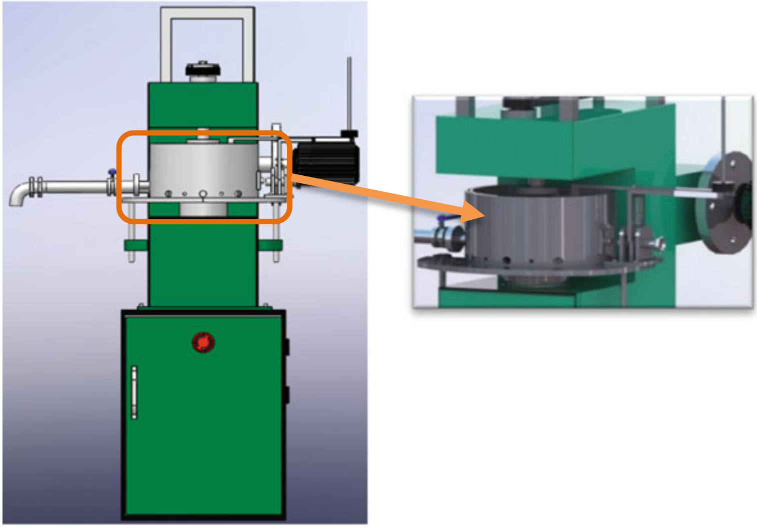


Fig. 2 Front view of tool chip tribometer with enlarged view of the tank

operation is performed. In this instrument, there are three main components such as disc, tool, and pin. It consists of a disc which is mounted inverted rotates at a preset speed. It consists of a tool that can remove a layer of the disc material. The thickness of the layer removed depends on the feed given. It also consists of a pin on top of which a ball is mounted to measure the coefficient of friction. The pin remains stationary at the given position. The experiments are conducted on aluminium disc. The pin material chosen is the same as that of the material of drill (HSS) used for drilling the holes (Fig. 2).

5 Results and Discussion

See Fig. 3.

5.1 Drilling Results

Drilling is performed at three different speeds of 355, 710, and 1120 rpm at a constant feed rate of 10 mm/min. The reason for selecting these particular speeds and feed ranges is due to the machine capability. For performing the drilling operations, five different cutting environments are chosen such as Dry, De-ionized water, Commercial (Koolkut) emulsion, Neem emulsion, Neem + IL emulsion. Each experiment is

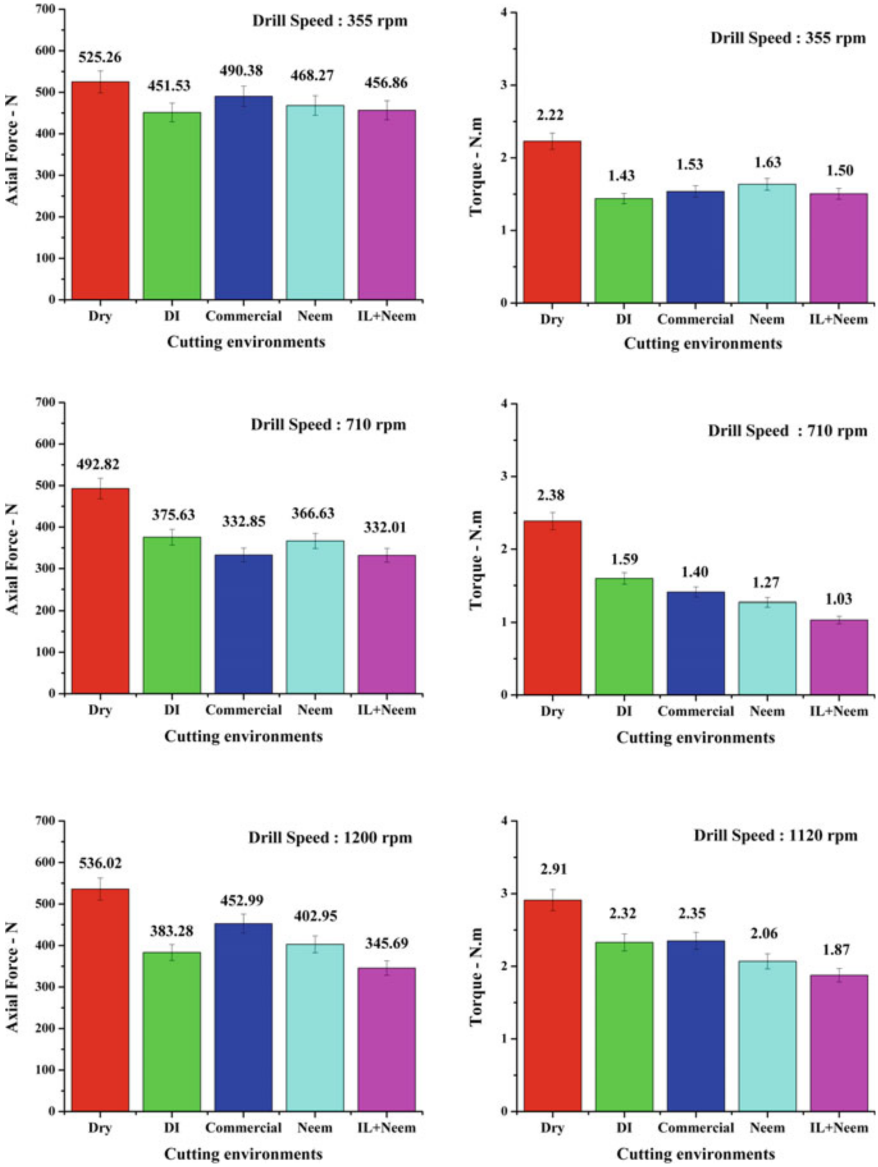


Fig. 3 Bar charts depicting the drilling performance with different cutting environments

repeated thrice and the average values are reported. The variation of the results is represented in the bar graphs.

From Table 1, it can be observed that the percentage reduction in Axial force and Torque for Neem with IL emulsion with respect to commercial emulsion are highest

Table 1 Comparison of Axial force and Torque for three different cutting speeds

Speed in rpm	Emulsion	Axial force in Newton	Torque in Newton-meter
355	Commercial	490.38	1.53
	Neem with IL	456.86	1.50
	% reduction	*6.83*	*1.96*
710	Commercial	332.85	1.40
	Neem with IL	332.01	1.03
	% reduction	*0.25*	*26.42*
1120	Commercial	452.99	2.35
	Neem with IL	345.69	1.87
	% reduction	*23.68*	*20.42*

in case of drill speed at 1120 rpm which are 23.68% and 20.42%, respectively which is due to the formation of tribofilm at the interface of the tool and workpiece.

5.2 Tool Chip Tribometer Results

Five different cutting environments are chosen such as Dry cutting, De-ionized water (DI), Commercial (Koolkut) emulsion, Neem emulsion, and Neem with IL emulsion. Three different speeds of disc revolution are chosen such as 30, 70, and 100 rpm. Each experiment is repeated thrice and the average values are reported. The variation of results is depicted using the bar graphs represented in the bar charts (Figs. 4, 5, and 6).

From the results, it can be observed that the emulsions made of Neem + IL has shown the least coefficient of friction when compared with other cutting environments. There is a 43% reduction in coefficient of friction for Neem + IL emulsion

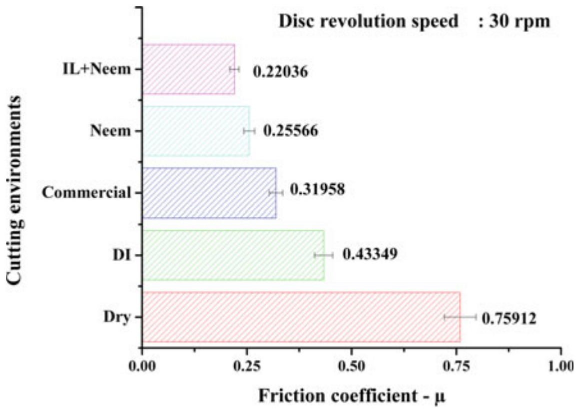


Fig. 4 Comparison of friction coefficient for different cutting environments for disc speed of 70 rpm

Fig. 5 Comparison of friction coefficient for different cutting environments for disc speed of 30 rpm

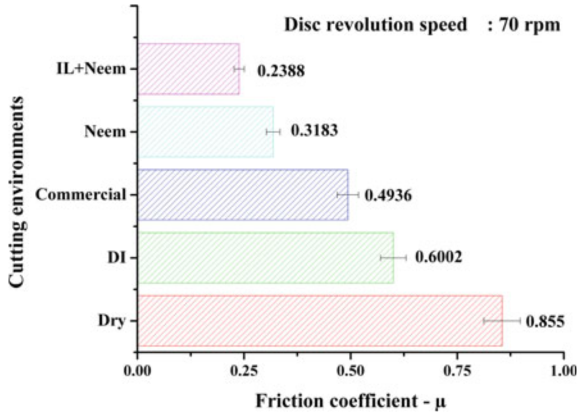
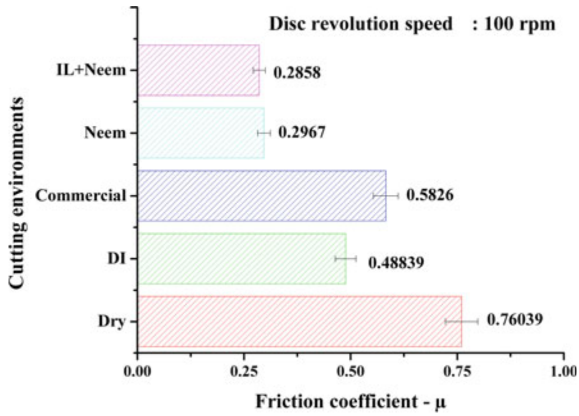


Fig. 6 Comparison of friction coefficient for different cutting environments for disc speed of 100 rpm



when compared with that of commercial cutting environment for the disc is revolution of 30 rpm. The percentage in reduction of friction coefficient for Neem + IL when compared to the commercial cutting environment for a disc revolution speed of 70 rpm is 106% whereas the same for disc revolution speed of 100 rpm is 103.84%. Thus, the Neem + IL emulsion can be used as an alternative to the commercial cutting fluid in the tribological point of view. It can be concluded that Neem with IL in comparison to the commercial cutting fluid is a better cutting fluid with respect to the average surface roughness at 100 rpm of the disc revolution showed a significant reduction of 11.7% which may be attributed to better flowability characteristic of the Neem with IL emulsion to the interface of workpiece and tool.

5.3 Surface Roughness Analysis

See Figs. 7, 8, 9, 10, 11, and 12.

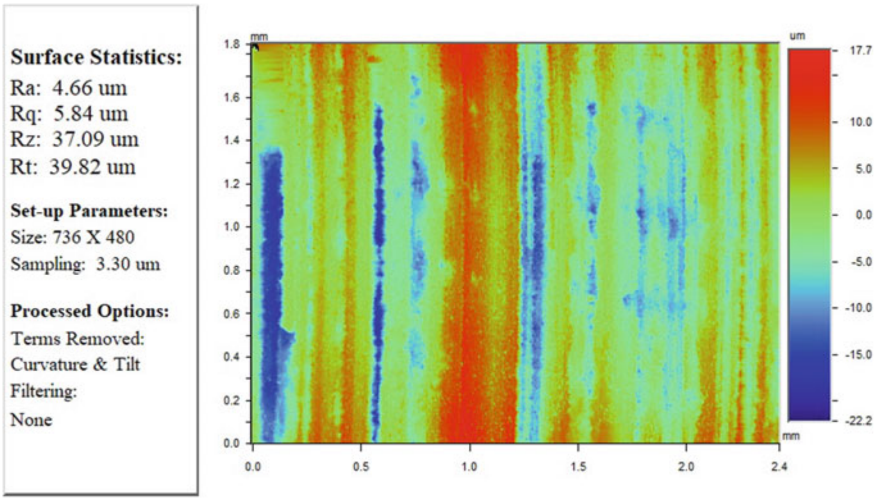


Fig. 7 Surface roughness of the disc after cutting when commercial emulsion used as cutting fluid with disc revolution speed of 30 rpm

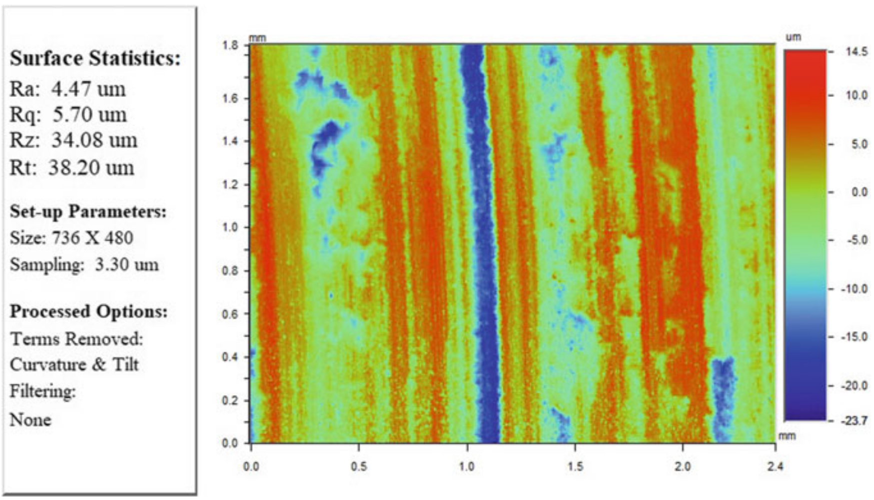


Fig. 8 Surface roughness of the disc after cutting when Neem with IL emulsion used as cutting fluid with disc revolution speed of 30 rpm

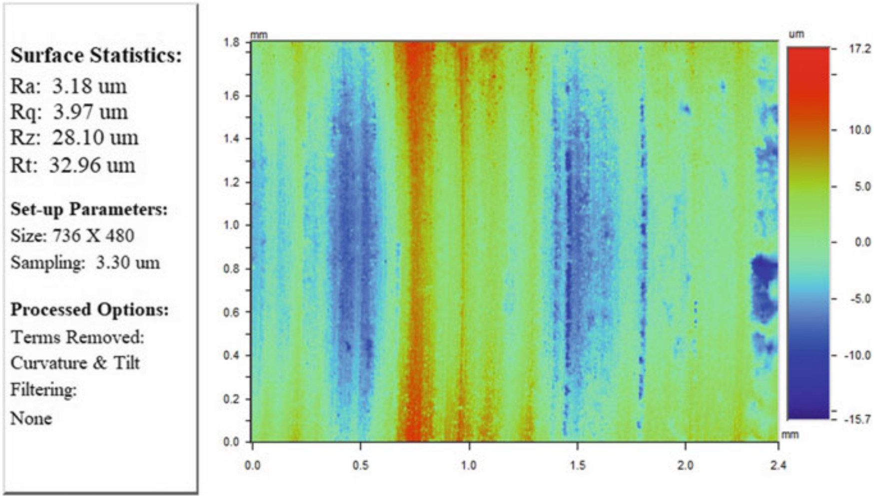


Fig. 9 Surface roughness of the disc after cutting when commercial emulsion used as cutting fluid with disc revolution speed of 70 rpm

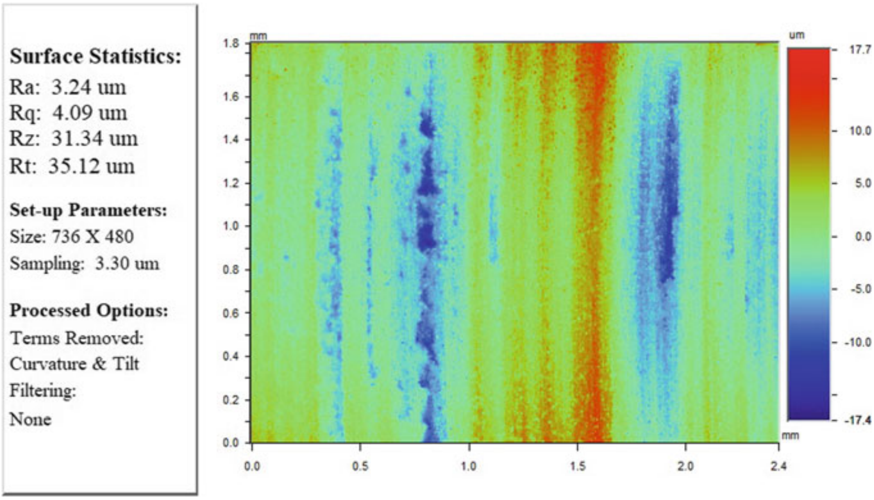


Fig. 10 Surface roughness of the disc after cutting when Neem with IL emulsion used as cutting fluid with disc revolution speed of 70 rpm

6 Conclusions

Significant improvement in the performance of Neem + IL emulsion when compared with Commercial emulsion has been observed which can be summarized as follows: Table 2

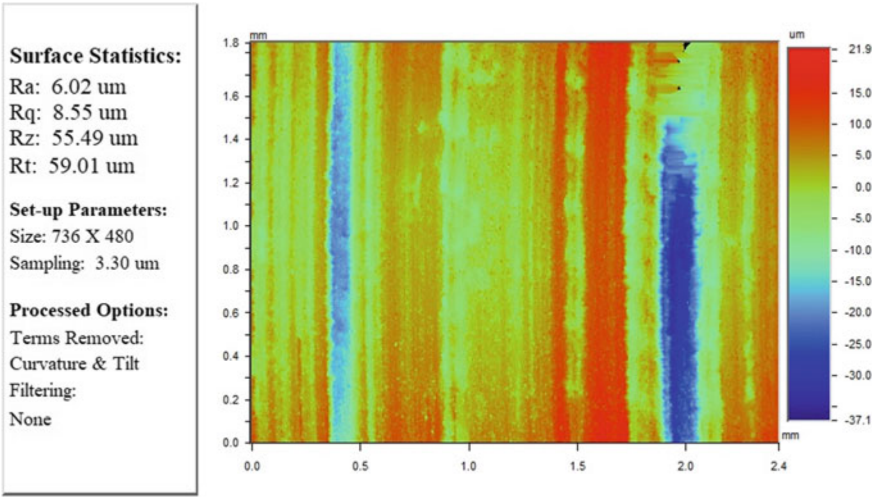


Fig. 11 Surface roughness of the disc after cutting when commercial emulsion used as cutting fluid with disc revolution speed of 100 rpm

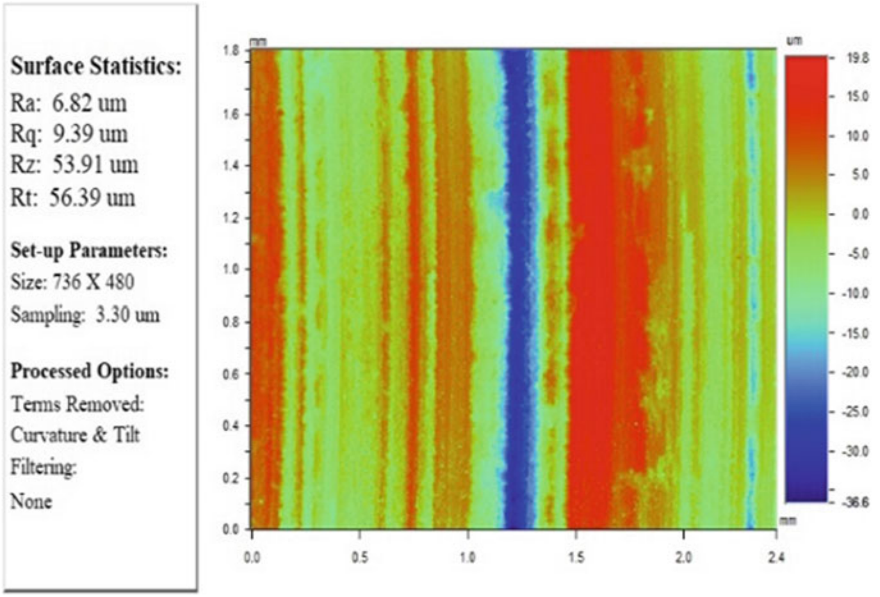


Fig. 12 Surface roughness of the disc after cutting when Neem with IL emulsion used as cutting fluid with disc revolution speed of 100 rpm

Table 2 Summary of the performance of Neem + IL as cutting fluid with different parameters

Parameter	Percentage reduction (%)
Axial force @ 1120 rpm	23.68
Torque @ 1120 rpm	20.42
Coefficient of friction @ 70 rpm	106
Surface roughness @ 100 rpm	11.7

Hence, it can be concluded that the emulsion made of Neem + IL is one of the best eco-friendly alternatives for commercial cutting fluid in terms of machining Performance, Tribological Performance, and Finishing requirements.

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Supply Chains

Adaptive Inventory Replenishment for Dynamic Supply Chains with Uncertain Market Demand

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Abstract The flow of goods in supply chains starts from production plants to regional warehouses to local distribution centers and from these local distribution centers to point of sale at retail outlets. Uncertainties in global market such as trade wars and extreme weather conditions disrupt the flow of goods in the global supply chains. This paper presents a reinforcement learning approach for an autonomous inventory replenishment planning model that attempts to capture few aspects of the goods such as market demand, costs associated with the inventory, product life cycle, and/or seasonality along with a set of inventory policies. The proposed model has been evaluated using two different time horizons viz., weekly and monthly, and it is observed from our simulation runs that monthly planning provides around 30% cost reductions compared with weekly planning, and the algorithm is found to select the right policy in about 85–95% of the times across the experiments.

Keywords Inventory · Demand uncertainty · Replenishment · Reinforcement · Learning · Supply chains

1 Introduction

The supply and distribution chains that enable shipment of goods from manufacturing source to end customer locations have seen larger transformations over the last few decades. Supply chains have evolved to enable organizations to manufacture products with larger product variety to meet individual customer preferences as well

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A. Chakrabarti and M. Arora (eds.), *Industry 4.0 and Advanced Manufacturing*, Lecture Notes in Mechanical Engineering,
https://doi.org/10.1007/978-981-15-5689-0_28

as act as a catalyst to provide technological innovation as perishability of the goods is more acceptable irrespective of the nature of the product or the commodity. The concept of perishability inherently refers to product life cycle dimension rather than taking it literally for the product perishability definition. Inventory control effectively contributes to significant amount of the total supply chain costs, and over the last decade, the combination of the factors such as market demand, inventory costs, changing customer preferences, and many other factors has ensured that many products do have minimal life cycle length of few years rather than decades. Chen et al. [1] present a case-based multi-criteria ABC analysis including factors such as lead time and criticality of SKUs that provides more flexibility in classification of SKUs. Jiang and Sheng [2] present a case-based reinforcement learning algorithm for dynamic inventory control in a multi-agent-based supply chain system with the premise that traditional time-triggered and event-triggered ordering policies become inaccurate causing excessive inventory (cost) or shortage. Kim et al. [3] employed the reinforcement learning algorithm for attaining a satisfactory service level in n-echelon supply chain. Hsueh [4] explores the effects of product life cycle on inventory control in manufacturing/re-manufacturing system and determines optimal production lot size, reorder point, and safety stock during each phase of product life cycle. Sun and Zhao [5] in their paper model Q-learning algorithm as a reinforcement learning approach for specifying ordering policies of the supply chain with five stages. In another work, Mortazavi et al. [6] use an agent-based simulation technique integrated with a reinforcement learning algorithm for a four-echelon supply chain that faces non-stationary customer demands. Kara and Dogan [7] address the inventory management problem of perishable products and present a reinforcement learning which is used in their research work, and the policies are optimized using Q-learning and Sarsa algorithms.

The markets are connected globally with enhanced visibility and ensuring that multiple nodes in the supply chain are sufficiently proactive. Push- and pull-based strategies in supply chain flows help organizations to carve out strategic and tactical plans based on market needs. A push-based supply chain, where upstream nodes drive the inventory flows, is used when the products or goods have low demand uncertainty. Pull-based strategy, where the downstream nodes pull inventories from upstream node, is used when products have high demand uncertainty. Baryannis et al. [8] provide a comprehensive review of supply chain literature that addresses problems relevant to SCRM using approaches that fall within the AI spectrum. Lolli et al. [9] use supervised classifiers based on the machine learning to perform a limited exhaustive search to define the best reorder policies per item by presenting the lowest cost classification of in-sample items. Priore et al. [10] employ an inductive learning algorithm for defining the most appropriate replenishment policy over time by reacting to the environmental changes in a three-echelon supply chain where the scenario is defined by seven variables viz., cost structure, demand variability, three lead times, and two partners' inventory policy.

This motivation of the research is to study and explore insights into dynamism and uncertainties in inventory management at various echelons in supply chain considering various factors such as market demand, costs associated with the inventory flow, product life cycle, and/or seasonality along with a set of inventory policies. The research problem requires use of data and decision support models to foresee and predict uncertainties, capture the nature of the uncertainties, and provide model-driven decisions using intelligent learning algorithms to get adaptable answers to respond to practical needs. Little amount of work has been published in scientific journals/conferences considering combinations of factors related to products such as seasonality, life cycle, demand behavior, and planning horizon in relation to autonomous and dynamic selection of inventory policies over time. Dynamic selection essentially means that the system by itself selects the right inventory policy based on demand projections without manual intervention using reinforcement learning approach. The paper proposes replenishment system where manual intervention is almost minimal or non-existent which is applicable from a warehouse or distribution center in a supply chain. This same is perfectly applicable for an autonomous retail store. The paper is organized as follows. Section 2 introduces the inventory replenishment model detailing replenishment policies, states and actions considered for our study. The reinforcement learning algorithm based on Q-learning approach is presented in this section. Section 3 details out the simulation runs and experiments of our study followed by conclusion and scope for extended research.

2 The Replenishment Model

2.1 Problem Definition

The pull-based supply chain model is defined for our study that necessitates individual nodes in the supply chain to adopt right set of inventory replenishment policies for managing inventory flows from upstream supplies to satisfy the demand requirements downstream in the supply chain. The nodes could be either a central warehouse or local/regional distribution centers or point-of-sale outlets. Each of these nodes does handle good amount of products with each of these products having its own demand behavior, replenishment cycles, minimum and maximum order quantities, product life cycle, and seasonal or cyclical trends. In this work, we pick up one of the nodes in the supply chain say a distribution center and study the learning-based replenishment model considering the following assumptions.

1. Historical customer demand is generated using a compound Poisson process, where the size of the demand is defined to have the discrete uniform distribution.
2. Future demand data is generated using a time-series forecasting process, and any impact of market campaigns/promotions is incorporated into future demand profile.
3. Historical data is used for training the proposed model, and the future demand data is taken as one of the inputs to the autonomous replenishment model.
4. Order is placed for procurement with an order quantity Q that is defined based on the nature of the replenishment policy in operation.

5. Ordering cost or setup costs are incurred every time an order is placed.
6. Order can be replenished fully with an expected lead time L, and the standard deviation of lead time is defined as l.
7. Shortages in inventories are allowed, and the surplus inventories are carried forward to the next planning period.
8. Backorders are not considered, and shortages are assumed to be lost demand.
9. Joint replenishment between multiple products is not considered.
10. The life cycle of a product could be divided into the following phases: introduction (phase 1), growth (phase 2), maturity (phase 3), and decline (phases 4 and 5).

2.2 Inventory Policies

The following periodic and continuous review policies which are stock based were adapted and implemented in our simulation model. Stock-based inventory policies replenish inventory based on inventory levels at the replenishment centers based on market demand.

i. The periodic (R, S) policy, where every R time units (the review period) an order is placed to raise the inventory position to level S.
ii. The periodic (R, s, S) policy, where every R time units, an order is placed to raise the inventory position to level S provided the inventory position has reached or fallen below the reorder level s.
iii. The periodic (R, s, Q) policy, where every R time units an order of Q units is placed provided the inventory position is less than or equal to s.
iv. The continuous (s, S) policy, where an order is placed to raise the inventory position to level S when the inventory position falls to or below level s and
v. The continuous (s, Q) policy, where Q units are ordered when the inventory position falls to or below level s.

The values of maximum inventory position S are defined for our experiments as the maximum or average of weekly demands observed over the past historical demand periods, and Q can be computed using economic order quantity (EOQ) formulae or can be set to be equal to the expected forecast demand in the future time periods. EOQ works well when the demand is more or less flat with no trend or seasonality.

2.3 States and Actions

The following set of propositions is introduced to enable the proposed model to learn and train itself over the historical data in a supervised manner to enable us to set the algorithmic configuration parameters. These propositions are characterizations obtained from the above-mentioned five policies to estimate reorder quantity, number of reorder points, under and overstocking implications, and demand behavior.

Proposition 1 Increase in inventory holding cost necessitates re-computation of reorder quantity, i.e., minimization of reorder quantity.

Proposition 2 Increase in set up costs necessitates minimization of number of reorders which eventually turns out increasing the reorder quantity for each order.

Proposition 3 Overstocking in inventories results in a need to move from periodic review policy to continuous review policy.

Proposition 4 Continual shortages in inventories require a shift from periodic review policy to continuous review policy.

Proposition 5 Change in demand behavior from flat pattern to an increasing or decreasing trend requires switch to a continuous review policy.

Proposition 6 Change in demand behavior to the flat pattern from increasing or decreasing trend requires switch from continuous to periodic review policy.

Proposition 7 Demand in maturity phase of the product with flat pattern can be fulfilled with periodic review policy.

The last two propositions essentially imply that it uses combination of either surplus or shortages in inventory with demand trend.

2.4 Reinforcement Learning Algorithm

Reinforcement learning (RL) provides an alternative approach to solve difficult control problems which are impossible to solve using supervised learning and traditional dynamic programming methods [11]. RL algorithms usually estimate the value functions of Markov decision process by observing state transition data. Tabular algorithms such as tabular Q-learning and tabular Sarsa-learning have be widely studied. In tabular RL algorithms, value functions are represented and estimated in tabular forms for each state-action pair [11]. In our work, we use the combination of shortages (*avg shortage*), frequency of shortages (*freq shortage*), and surplus (*avg surplus*) inventories over the past ***n*** periods to trigger the need for evaluation of policy change. An adaptation of Q-learning algorithm is used in our reinforcement learning process to select and use the mentioned replenishment policies in our model. The following notations are defined before presenting the algorithm.

Action	An array that contains different inventory policies that can be applied.
s	The policy index.
A	The action index.
Reward	The associated costs
S_t	The *state* tuple which represents an array containing average shortage, frequency of shortages, and average surplus during a time period.
Policy	A dictionary that maps an action to a state.
Returns	The reward which is the total cost incurred.
state_action_reward	An array that keeps track of the states, actions, and their corresponding rewards.
state_action_return	An array that contains the mean episodic reward for the specified time period.
seen_action_state	An array containing the state-action pairs that have been visited already. It is used as a caching mechanism.
DISCOUNT_FACTOR	A factor that is set to 0.9 to ensure that the RL algorithm places higher weightage on long-term rewards. (Values closer to 1.0 are used to 'discount' the immediate reward)
EPSILON	A factor used to balance exploration and exploitation by assigning a 20% chance to choose a random inventory policy.
Demand	An array containing the forecasted demand values.
G	The reward for an episode.
Q	The Q-table which contains the reward for each action taken in each state
V	Contains the maximum return corresponding to the best action for a given state in the Q-table

We use the following symbols:

- { } to refer to dictionaries or key-value pairs.
- () to refer to sets where only unique elements are permitted.
- [] to refer to arrays.

Reinforcement Learning Algorithm

1. Initialize variables
   policy = {},
   Q = {},
   returns = {},
   actions = set of all inventory policies under consideration,
   state_action_reward = [],
   DISCOUNT_FACTOR = 0.9,
   EPSILON = 0.2
2. for time period *t* in *Demand*:
   a. S_t = [*avg shortage*$_t$, *freq shortage*$_t$, *avg surplus*$_t$]
   b. If random(0, 1) < (1 – *EPSILON*)
      i. *action* = *policy*[*S*]
   c. else: *action* = random(*actions*)
   d. *reward* = -1 x *cost*$_t$
   e. if end of *Demand* has been reached:
      i. *state_action_reward.append*([S_t, null, *reward*])
      ii. break
   f. else:
      i. *state_action_reward.append*([S_t, *action*, *reward*])
   g. *G* = 0, *state_action_return* = []
   h. for *state, action, reward* in reversed(*state_action_reward*)[1:]:
      i. *state_action_return.append(*[*state, action, G*])
      ii. *G* = *reward* + *DISCOUNT_FACTOR* x *G*
3. *seen_state_action* = ()
4. Loop until *Q*[*s*] converges:
   a. for *state, action, G* in *state_action_return*:
      i. if [*state, action*] not in *seen_state_action*:
         1. returns[[*state, action*]].append(G)
         2. Q[s][a] = mean(returns[[*state, action*]])
         3. *seen_state_action.append*([*state, action*])
   b. for *s* in *policy.keys*():
      i. policy[s] = argmax(Q[s])
5. *V* = {}
6. for *s* in *policy.keys*():
   a. V[s] = max(Q[s])
   b. return V, policy

In our implementation, the values of average shortages, frequency of shortages, and average surplus are pre-estimated based on training data set with a planning horizon of *n* periods considering the cost vs benefit trade-off for the mentioned five policies. The forecast data together with the historical data is eventually used on the rolling window basis to decide the need for trigger for the policy change. Any significant change in the cost data (i.e., ordering costs and holding costs) necessitates the recompilation of the state-action transition matrix using the historical as well as forecast data to redefine the selection of policies.

3 Simulation Runs and Experiments

The objective of our experiments is to ensure that the demand is satisfied at stated service levels, and shortages are avoided as much as possible with simultaneous minimization of total costs. Total cost comprises total annual ordering costs and annual inventory holding costs. The following three demand patterns are simulated to experiment and validate the proposed model:

1. Demand being flat and increasing.
2. Demand decreasing and turns flat.
3. Considering the complete product life cycle with four phases.

Demand forecast is assumed to be given on daily basis for the next one year planning period using historical data for the last three to five years. Inventory holding cost is assumed to be defined at 5% of the product cost. Product cost is assumed to be \$10 for our experimental runs using simulated data for training out models. Ordering costs are defined as 10% of the cost of the reorder quantity. Experiments for policy definitions are performed at weekly and monthly planning horizon granularity levels.

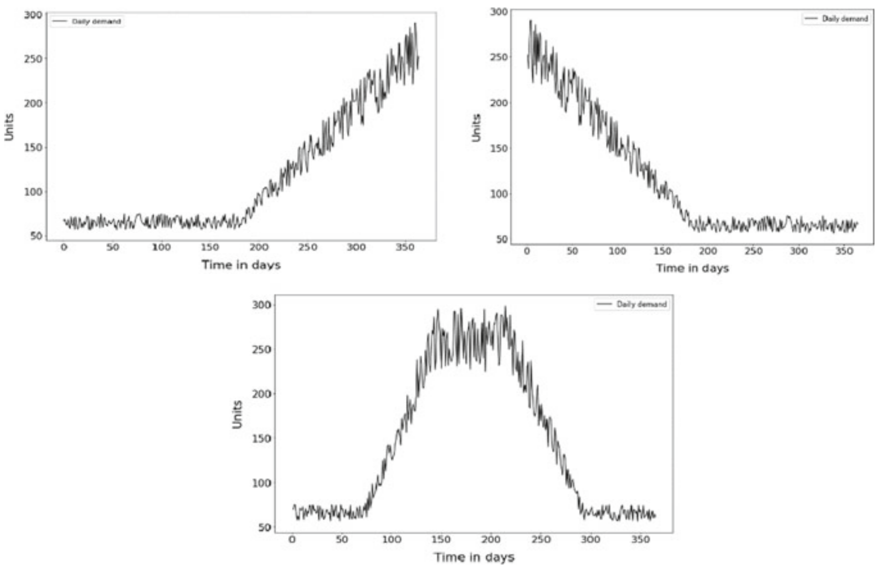

Fig. 1 Three types of demand profiles

Table 1 Evaluation of costs at weekly run

Demand profile	Total costs	Average surplus	Average deficit
Flat and increasing	2702554.18	187.98	43.23
Decreasing and flat	3942057.90	229.19	42.25
Full product life cycle	1234665.63	170.20	83.53

Table 2 Evaluation of costs at monthly run

Demand profile	Total costs	Average surplus	Average deficit
Flat and increasing	2006172.33	1069.73	34.76
Decreasing and flat	2489461.39	1187.54	34.90
Full product life cycle	1849730.37	1063.63	77.81

The three presented scenarios (Fig. 1) have been extracted from the historical profiles of the products from consumer product company supply chain at the local distribution center that receives supplies on either weekly or monthly basis, while the deliveries to different retail outlets happen on daily basis based on the orders received from the retail outlets across a major metropolitan city in India. The reinforcement learning algorithm together with inventory models and policies is implemented in Anacondo Phython 3.7 programming language and PostgreSQL. Tables 1 and 2 presents the total annual costs (includes ordering cost and inventory carrying cost), average daily surplus, and average daily deficit for weekly and monthly planning models with the average of the results presented over 10 simulation runs for three selected product profiles over an yearly planning cycle. The cumulative demand for each demand profile is kept constant for with respect to each one of the demand profiles and their corresponding simulation runs.

Figures 2 and 3 present the computation of surplus and shortages for the three demand profiles over weekly and monthly planning horizon for one simulated demand scenario. The results are presented for service levels 95% service levels. The inventory carrying costs are computed on daily basis, while ordering cost is defined for each order placed for procurement. Average surplus and shortages presented in the tables are computed using the end of the week/month surpluses and shortages in inventory. We found that the proposed algorithm is observed to select 85–95% of the times the right policy in our experiments and in those cases where the selection was a mismatch got corrected within a period length of 2 weeks in the worst case.

The proposed approach looks into the future demand profile and revises the order quantities placed with the upstream supplier based on surplus and shortages in inventory on-hand. It was observed from our experiments that when the demand is flat

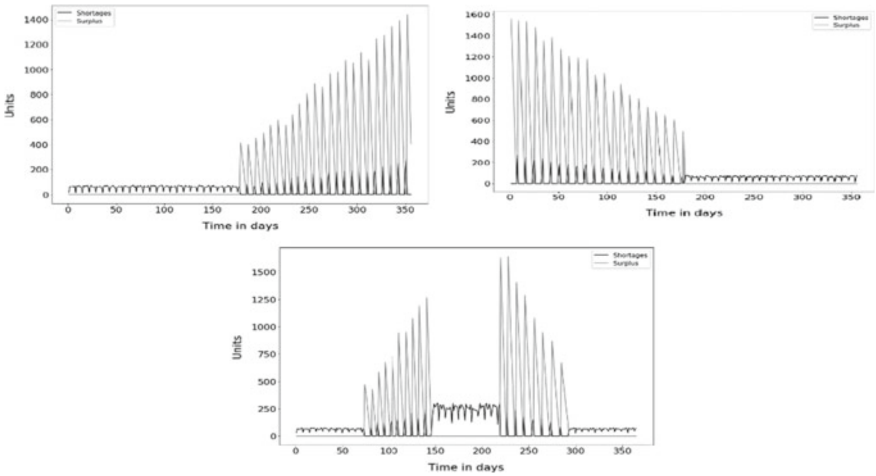

Fig. 2 Surplus and shortages for weekly planning mode for the demand profiles

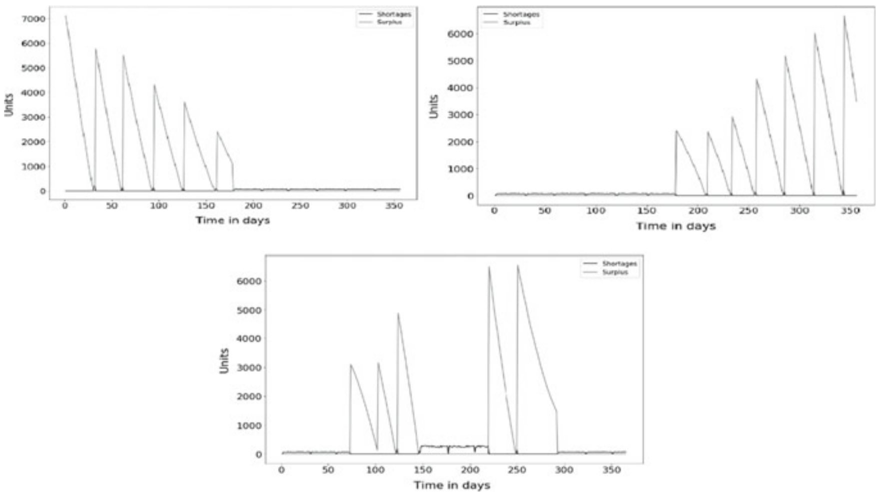

Fig. 3 Surplus and shortages for monthly planning mode for the demand profiles

over a period of time (*R*, *S*), policy was found to be working well. (*R*, *s*, *S*) or (*R*, *s*, *Q*) was found to be working good under the conditions of demand uncertainty, and (*s*, *S*) or (*s*, *Q*) is found to be working well under conditions of increasing or decreasing demand.

The higher service levels introduced in our experimentations resulted in higher surplus scenarios during the periods of increasing and decreasing demand profiles. It is found that weekly planning model is cost effective for all the demands profiles.

4 Conclusions

In this work, we attempt to introduce a replenishment model using a supervised learning-based approach that reflects the characteristics of the inventory operations in a typical supply chain and validate the results against three demand scenarios that are quite evident in real life. The proposed model considers multiple factors such as product life cycle, demand behavior and seasonality, planning horizon granularity along with set of replenishment policies to cost effectively plan and define replenishment cycles, and order quantities considering lead time variations. This essentially automates the replenishment process to a good extent and enables operations of autonomous warehouses in supply chains or motivates to run autonomous retail stores. The presented work limits the study for evaluation of replenishment model with no back orders, and shortages are allowed which need not be true in many practical scenarios. The research can be further extended considering perishable products, joint replenishment options, as well as policies considering back orders, supply variations, market campaigns, etc.

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