Abstract: Drilling is a salient machining process employed in assembling the components and structures made from polymer composites. Influence of various drilling process parameters on the drilling process has been identified and controlled to maintain the integrity of the composite material and avoid material damage during drilling. The precision of drilling depends upon many process parameters like feed rate, tool material, cutting speed, drill diameter, fiber orientation in composite material and thrust forces developed. The present investigation deals with the study and evaluation of influence of drilling parameters such as material thickness, drill diameter, drill point angle, feed rate and spindle speed on thrust force developed during drilling of glass fiber reinforced plastic composite laminates using Taguchi method. The experimental results prove that drill angle and the spindle speed are the most significant parameters which influence the thrust force. The simulation of the drilling process was developed using a novel system dynamics (SD) modelling approach through a causal loop diagram. Design of experiments
(DOE) was utilized to generate a number of experiments required. A full factorial
design is used, and 243 holes were drilled to collect the experimental data. The
required mathematical equation for modelling was developed by using DOE
method. To validate the SD results, the results obtained through SD novel approach
were compared with artificial neural network and response surface method which
are recognised as the best simulation tools and noticed a good agreement between
the values obtained. The novel SD approach of modelling showed an agreement of
more than 93% acceptance level with the experimental results.

Subjects: Mechanical Engineering; Manufacturing Engineering; Materials Science;
Keywords: artificial intelligence; response surface method; system dynamics; drilling;
composites; thrust force

1. Introduction
Glass fiber–reinforced plastic (GFRP) composites find a wide range of application in the industries like
automotive, marine and aerospace due to their significant mechanical, tribological and thermal
properties (ASM Handbook., 2002). Glass fibres are extensively utilized as the reinforcement for the
polymeric resins, particularly with epoxy and polyester. Though the glass fibre possesses a low stiffness
compared to its counterparts, it possesses the unique advantage of combining low density with
high strength. Moreover, glass fibres also have an economic advantage over carbon and aramid
(Kevlar) fibres. Thus, it shall continue to be used as a prime reinforcing material even in the futuristic
applications of composites (Al-Malaika, Axtell, Rothon, & Gilbert, 2017). The incorporation of glass
fibres as reinforcement to polymers increases the tensile strength, creep resistance, flexural modulus,
impact resistance, chemical resistance and dimensional stability (Pihtili & Tosun, 2002).

The research has proved the E-glass to be strong enough to be used in composites for making armour (4, 5). Machining of these composite materials is critical and exhibits certain problems such as
delamination, shrinkage, fiber pull-out, degradation, etc., owing to their heterogeneity and anisotropic
behaviour (Hu & Liu, 2010; Tagliaferri, Caprino, & Diterlizzi, 1990). Drilling is a salient machining process
employed in assembling the components and structures made from polymer composites. The defects
causd in composite laminates due to the drilling process result in lowering the load-bearing strength
and durability (Wong, Wu, & Croy, 1982). The application demands for drilling of quality holes in GFRPs;
however, researchers have identified that delamination in the GFRP laminate composites is a major
limiting factor. The accuracy of drilling process to obtain a good quality drill is influenced by the thrust
force, which is affected by variables, such as drill geometry, drilling speed and feed rate, produced
during drilling (Dixit, Pal, Kapoor, & Stabenau, 2016; Jain & Yang, 1993; König & Grass, 1989; Linbo,
Lijiang, & Xin, 2003; Ramkumar, Aravindan, Malhotra, & Krishnamurthy, 2004; Wang, Wang, He, &
Yang, 1998). An attempt has been made by researchers to limit the thrust force by varying and
optimizing drilling parameters through simulations and experiments. The numerical methods with
mathematical equations are developed in 3D space and utilized for geometrical calculations of the
drilling procedure (Bagci & Ozcelik, 2006; Kadigama, Abou-El-Hossein, Mohammad, Al-Ani, & Noor,
2008; Vijayaraghavan & Dornfeld, 2007; Zitoune & Collombet, 2007). The finite element analysis and
a numerical approach are carried out based on the Lagrangian and Eulerian methods (Bagci & Ozcelik,
2006; Dixit et al., 2016; Kadigama et al., 2008; Linbo et al., 2003; Ramkumar et al., 2004;
Vijayaraghavan & Dornfeld, 2007; Zitoune & Collombet, 2007).

Patwari et al. investigated the effect of feed rate (100, 300 and 500 mm/min), speed (500, 750 and
100 rpm) and drill tool diameter (6, 9 and 12 mm) on the surface roughness of GFRP with and without
the presence of electromagnetic waves. The study comprising Box-Behnken (Bagci & Ozcelik, 2006)
experiments indicated that the machining in the presence of electromagnetic waves improves the
surface roughness of the drilled hole. Though the authors present the case of using the
electromagnetic waves and prove the fact that the application of magnets improves the drilling quality, there is no explanation provided as to how the magnetic effect is affecting the non-ferrous GFRP material. There is also no mention of the type of glass fibre and matrix material used in the work. Therefore, the results obtained lose its credibility (Patwari, Yusuf, & Ferdous, 2019).

Shahkhosravi et al. investigated the impact of high-speed drilling parameters on the delamination during GFRP drilling and subsequently on the static strength and fatigue life of woven glass fibre-reinforced epoxy composite laminates (Shahkhosravi, Yousefi, Najafabadi, Burvill, & Minak, 2019). Acoustic emission technique was used to determine the delaminated zone, and the delamination factor was calculated using the Davim’s adjusted model, which very well accommodates the damaged area and the major crack length. The experiments were conducted at high speeds (3000, 6000 and 10000 rpm) and with the feed rates (50, 100 and 150 mm/min). It was found that the extent of cyclic load-induced delamination decreases as the hole cutting speed increases or as the feed rate decreases. The article is a potential research work but lacks the development of mathematical modelling for predicting the damage in the composite. In addition, the type of delamination measured in the work is not clear.

Forrester (1995) from the Massachusetts Institute of Technology, Cambridge, is the founder of the field of system dynamics (SD). SD is a method for studying the world around us. It helps us to better understand the causes of interesting or surprising behavior, whether social or technological, or both. It also helps us to find solutions to persistent problems. The behavior under study is not only interesting or surprising, but also undesirable. SD can be used to find ways to improve that behavior. Nowadays, SD finds huge applications in the management sector. For the first time, we made an attempt to introduce the SD as a simulation tool in the field of machining process. SD is an easier and effective tool in comparison with artificial neural network (ANN) and response surface method (RSM) as it involves simple model building approach, which does not consist of any programming. SD simulation in manufacturing dynamics has been extremely effective and has been in use for several decades. Oyarbide et al. have used SD in the simulation of production design for modelling and simulating the engine production facility (Oyarbide, Baines, Kay, & Ladbrook, 2003).

In the present investigation, novel SD modelling and simulation approach is used to simulate the thrust force and the process parameters influencing the overall drilling process, so as to select optimum thrust force to reduce delamination and produce quality holes.

2. Materials and methods

2.1. Materials

The materials used included the E-glass chopped strands as reinforcement material of density 2590 kg/m$^2$ and modulus of elasticity of 72.5 GPa. The matrix material used is general-purpose epoxy resin. The E-glass fibres were reinforced with resin matrix in 44% volume fraction. The recommended methyl ethyl ketone peroxide is used as a hardener. Hand layup process was used to fabricate the GFRP composite sample specimen. Figures 1 and 2 show the prepared specimen and drilled specimen.

2.2. Machining of GFRP composites (drilling)

The drilling of GFRP composite laminate was conducted using 3-hub TRIAC CNC machine as shown in Figure 3. Solid carbide drills were used to drill holes since they possess a very minimum wear rate. During the drilling process, thrust force was measured using Kistler dynamometer and charge amplifier. The mean values of the force generated were tabulated from the data collected in dynoware format.

The process parameters considered for machining (drilling) of the GFRP composite laminate considered in the study are shown in Table 1. Taguchi full factorial design was used to select the
optimum number of experiments through design of experiments. Level 1, Level 2 and Level 3 with varied process parameters were considered.

3. Results and discussion

3.1. Analysis of variance for thrust force

The one-way analysis of variance (ANOVA) test was used to find significant parameters with the confidence level of 95%. The results of ANOVA test, shown in Table 2, indicate that drill point angle and the spindle speed significantly influence the thrust force. The results obtained also indicate that the combination of the parameters like speed and diameter and speed and drill point angle effects the cutting force significantly.
3.2. Taguchi method used to optimize the thrust force
The mean values of the thrust force response generated are shown in Table 3. The analysis is performed considering smaller value is the better one for optimization in the present study. It is observed that drill angle (DA) followed by spindle speed (SS) have the lowest values.

### Table 1. Factors and levels

| Factor          | Level 1 | Level 2 | Level 3 |
|-----------------|---------|---------|---------|
| A: TS—tool speed (rpm) | 900     | 1,200   | 1,500   |
| B: FR—feed rate (mm/min) | 75      | 110     | 150     |
| C: DD—drill diameter (mm) | 6       | 8       | 10      |
| D: DA—drill angle (deg) | 90      | 103     | 118     |
| E: MT—material thickness (mm) | 8       | 10      | 12      |

### Table 2. ANOVA for thrust force

| Source      | DF | SS     | MS     | F     | P   |
|-------------|----|--------|--------|-------|-----|
| DA          | 2  | 7,729.08 | 3,864.54 | 1,409.16 | 0   |
| DD          | 2  | 875.17  | 437.59 | 159.56 | 0   |
| MT          | 2  | 622.22  | 311.11 | 113.44 | 0   |
| SPEED       | 2  | 2,860.63 | 1,430.31 | 521.55 | 0   |
| FEED        | 2  | 159.58  | 79.79  | 29.09  | 0   |
| DA×DD       | 4  | 134.13  | 33.53  | 12.23  | 0   |
| DA×MT       | 4  | 18.27   | 4.57   | 1.67   | 0.16 |
| DA×SPEED    | 4  | 237.6   | 59.4   | 21.66  | 0   |
| DA×FEED     | 4  | 2.77    | 0.69   | 0.25   | 0.908 |
| DD×MT       | 4  | 26.17   | 6.54   | 2.39   | 0.053 |
| DD×SPEED    | 4  | 90.33   | 22.58  | 8.23   | 0   |
| DD×FEED     | 4  | 5.21    | 1.3    | 0.47   | 0.754 |
| MT×SPEED    | 4  | 9.84    | 2.46   | 0.9    | 0.467 |
| MT×FEED     | 4  | 1.89    | 0.47   | 0.17   | 0.953 |
| SPEED×FEED  | 4  | 47.9    | 11.97  | 4.37   | 0.002 |
| Error       | 192 | 526.55  | 2.74   | 0     |     |
| Total       | 242 | 13,347.3 | 3      |       |     |

DA, drill angle; DD, drill diameter; MT, material thickness; SS, spindle speed; MS: Mean squares; F: F Ratio; P: P value; DF: degrees of freedom.

### Table 3. Response table (Taguchi method)

| Level | DA | DD | MT | SS | FR |
|-------|----|----|----|----|----|
| 1     | 34.57 | 39.39 | 39.36 | 46.06 | 40.3 |
| 2     | 41.13 | 40.78 | 41.45 | 40.05 | 41.51 |
| 3     | 48.38 | 43.92 | 43.27 | 37.97 | 42.27 |
| Delta | 13.81 | 4.54 | 3.92 | 8.09 | 1.97 |
| Rank  | 1   | 3   | 4   | 2   | 5   |

DA, drill angle; DD, drill diameter; MT, material thickness; SS, spindle speed; FR, feed rate.
Thereby, it is very important to keep a check on the values of these parameters to be lowest possible to control and have minimum thrust force developed. The following parameters with a controlled value of drill angle (DA) = 90°, drill diameter (DD) = 6 mm, material thickness (MT) = 8 mm, drill speed (DS) = 1500 rpm and feed rate (FR) = 75 mm/min prove to be the best combination to achieve a lower value of thrust force.

3.3. Development of simulation model using SD approach
An SD approach using VENSIM model is used to simulate the thrust force considering the chosen input variable as DD, DA, DS, FR and MT. The response variable considered in relation is the thrust force. A connection between each variable and output variable is connected using VENSIM model by developing the causal loop diagram as shown in Figure 4. The causal loop diagram was generated by using the VENSIM software. A mathematical model that establishes a correlation between input/output variables is developed using MINITAB software and fed into the SD model. Hence, for the varied input variables, the SD model developed simulates the drilling process conditions in GFRP composite laminates and provides the value of thrust force developed.

3.4. System dynamics: Thrust force simulation
The MATLAB software was used to generate simulation plots for the thrust force versus drilling process variables considered in this study. Figures 5–7 show the simulation plots of thrust for various combinations of input variables. From the plot, it is clear that as the spindle speed increases, the thrust force decreases for the parameters DA and MT. It is also noticed that 90° DA, 6 mm MT and 75 mm/min FR yield less thrust force. In the same way, by plotting the graph for other variables and selecting the variables which give lesser thrust force value, an optimum combination of process can be obtained to achieve the minimum thrust force.

3.5. Validation of SD tool
The obtained results indicates the thrust force developed, for a controlled drilling process variable simulated using the SD modelling approach is validated using the most widely used simulation tools, ANN and RSM.

3.6. Artificial neural network
The single layer perceptron with single hidden layer is used in simulating the drilling process of GFRP composite laminates. The five nodes in the input layer as shown in Figure 8 correspond to the input variables DA, DD, MT, SS and FR, whereas the thrust force corresponds to one node output.
layer. The hidden layer (h), learning rate (\(\alpha\)) and the momentum rate (\(\mu\)) shall be optimized by hybridization of single hidden layer perceptron neural network) and genetic algorithm (GA).

ANN needs a set of training, testing and validation data. The fitness function of GA depends on the accuracy of classification of neural network. A customized MATLAB® code is generated. From the total data set of 243 input/output pairs available, 180 pairs were used for training and the remaining for testing and validation. The mean square error was set to \(1 \times 10^{-4}\). The three training parameters (\(h\), \(\alpha\) and \(\mu\)) corresponds to a real valued chromosome of length three units is selected in GA. The mutation rate and crossover selected were 0.2 and 0.6, respectively. Normalized geometrical ranking method was used to select the parent chromosomes.

\[
\text{Fitness} = \frac{\eta_{Trg} + \eta_{Tst}}{2} 
\]  

(1)
The expression for computing the prediction accuracy, $\eta$, is given in Equation (2), where $n_c$ is the number of correctly predicted neural network output values and $n$ is the total number of experiments (data) under consideration.

$$\eta = \frac{n_c}{n} \times 100$$  \hspace{1cm} (2)

A comparison of the results obtained is shown in Figure 9, i.e. thrust force by the methods used for modelling and analysis. SD and ANN show good agreement. Hence, the novel approach proves to be a robust method for drilling process optimization.
The data obtained from the SD model are compared with the experimental one to predict the acceptance level of the data obtained. The comparison is presented in Table 4. From the table, it is confirmed that the acceptance level between two data is above 93%. Hence, we can say that there is a good agreement between the data obtained from both the methods.

### 3.7. Response surface methodology

RSM is widely used for modelling and analysis of engineering problems. It is a statistical tool for the optimization of the process variable using the data collected. The RSM tool is used in the current study to optimize the response surface that influences various drilling parameters. Figure 10 shows a comparison of the results obtained using SD approach and RSM. A very close agreement in the results obtained from the two methods is observed when compared with the plot in Figure 8. Hence, it validates the application of SD as a tool to simulate the machining process.

Engin, Unal (2019) investigated the effect of feed (0.05, 0.075, 0.100 and 0.125 mm/rev), speed (200, 300, 400 and 500 rpm) and drill bit angle (118°, 125°, 130° and 140°) on the thrust force and cutting temperature generated during the GFRP drilling process. HSS drill bits of 8 mm diameter is employed in the work, and machining was carried out using CNC operated VMC (Engin, 2019). The full factorial design was used by the authors to create the experimental framework. Electronic load cells were utilised to measure thrust force, and thermocouples were used to determine the temperature. The results indicate that the thrust force was majorly affected by the feed, contributing 80.54% to the variance, and drill bit angle proved to be the highly significant factor in case of the cutting temperature. The article does not provide the details of the reinforcing glass fibre and matrix resin used in the work. The authors presented neither the experimental data nor the complete ANOVA result table. The significance of the parameter is given only based on the percentage contribution; therefore, the validity of the obtained result is questionable.

| Spindle speed (RPM) | Experimental thrust (N) | SD predicted thrust (N) | Acceptance level |
|---------------------|-------------------------|------------------------|------------------|
| 900                 | 34.890                  | 37.7075                | 93%              |
| 1,200               | 31.650                  | 33.6575                | 94%              |
| 1,500               | 29.580                  | 29.6075                | 99%              |
Agwa and Megahed conducted a multi-response optimization of cutting parameters: speed (160, 315, 500, 800, and 1250 rpm), feed (0.056, 0.112, 0.22, 0.315 and 0.45 mm/rev), and drill pre-wear values (0, 14, 22, 36 and 46 \times 10^{-4} g). The performance parameters used in the work were thrust, torque, and entry and exit delamination (Agwa & Megahed, 2019). The feed was found to be a dominant factor concerning the torque and exit delamination, whereas the pre-wear dominated the torque and entry delamination. A third-order regression model was suggested. The soft computing method using MATLAB was used to accomplish the multi-response optimisation. The work very well projects the single response optimisation through validated tests and higher-order analytical model having a high accuracy of prediction, but there is no model developed for the overall performance index.

4. Conclusions
Thrust force is a key factor influencing the propagation of delamination and is a major drawback faced in the drilling of GFRP composite laminates. The effective way is to simulate and optimize the drilling process parameters/variables that influence the thrust force to obtain good quality drilled hole without initiating delamination.

From the present study, the simulation results obtained show that

- The variables of drilling process simulated conclude that high speed machining, harder tool material and low feed rate influences reduction in thrust force, thus reducing the delamination in GFRP.
- The SD approach of modelling and analysis proves to be a robust method to simulate the thrust force developed during the drilling of GFRP.
- The results obtained from SD are validated with popularly used tool ANN and RSM. The results are in close agreement.
- The simulation plots help to identify the intermediate values, corresponding to the process parameters in considered range.
- Hence, SD proves to be an effective tool to simulate the drilling process.

Acknowledgements
The authors are grateful to the Department of Mechanical and Manufacturing Engineering, Manipal Institute of Technology, Manipal Academy of Higher Education, Manipal, for providing the lab facilities for the study.

Funding
The authors received no direct funding for this research.

Competing interest
All authors declare no competing interest.
Revati Borkhade
E-mail: revatiborkhade@gmail.com
Author details
B. R. N. Murthy1
E-mail: murthy.brn@manipal.edu
Vijay G.S1
E-mail: vijay.gs@manipal.edu
S. Narayan1
E-mail: s.narayan@manipal.edu
Nithesh Naik1
E-mail: nithesh.naik@manipal.edu
Department of Aeronautical and Automobile Engineering, Manipal Institute of Technology, Manipal Academy of Higher Education, Manipal, Karnataka, India.

References
Agwa, M. A., & Megahed, A. A. (2019). New nonlinear regression modeling and multi-objective optimization of cutting parameters in drilling of GFRP composites to minimize delamination. Polymer Testing, 75, 192–204. doi:10.1016/j.polymertesting.2019.02.011

Correction
This article has been republished with minor changes. These changes do not impact the academic content of the article.

Copyright and Reuse
The Author(s) 2019

Please cite this article as: Mechanical modelling and simulation of thrust force in drilling process in GFRP composite laminates: A novel system dynamics approach, B. R. N. Murthy, Vijay G.S, S. Narayan, Nithesh Naik, Nalokshman Sooriyaperakasam, Aravind Karthik & Revati Borkhade, Cogent Engineering (2019), 6: 1706981.

Acknowledgments
This work was supported by the Ministry of Education, Malaysia, under the Research University Grant No. UKM-FRGS/1/2018/UG56-001. The authors would like to thank the reviewers for their comments and suggestions which helped improve the quality of the paper.

Author details
B. R. N. Murthy1
E-mail: murthy.brn@manipal.edu
Vijay G.S1
E-mail: vijay.gs@manipal.edu
S. Narayan1
E-mail: s.narayan@manipal.edu
Nithesh Naik1
E-mail: nithesh.naik@manipal.edu

Department of Aeronautical and Automobile Engineering, Manipal Institute of Technology, Manipal Academy of Higher Education, Manipal, Karnataka, India.

Corresponding author
Vijay G.S
E-mail: vijay.gs@manipal.edu

Author details
B. R. N. Murthy1
E-mail: murthy.brn@manipal.edu
Vijay G.S1
E-mail: vijay.gs@manipal.edu
S. Narayan1
E-mail: s.narayan@manipal.edu
Nithesh Naik1
E-mail: nithesh.naik@manipal.edu

Department of Aeronautical and Automobile Engineering, Manipal Institute of Technology, Manipal Academy of Higher Education, Manipal, Karnataka, India.
