Experimental Study of CO_2 and Fiber LBM on SS316L and Optimization of Parameters using ANN

Tukaram Sargar[1], Aniket Jadhav[2], Nitish Kumar Gautam[3]

[1]Reserach Scholar, Shri Jagdishprasad Jhabarmal Tibrewala University, Vidyanagri, Jhunjhunu-333010, Rajasthan, India
*Corresponding author : Tukaram Sargar

[2]Assistant Professor, Department of Mechanical Engineering, Smt. Kashibai Navale College of Engineering, Pune-411041, India

[3]Assistant Professor, Department of Mechanical Engineering, Shri Jagdishprasad Jhabarmal Tibrewala University, Vidyanagri, Jhunjhunu-333010, Rajasthan, India

Abstract

The use of new advanced materials, such as advanced composites, ceramics, high strength steels and super alloys, presents several challenges for conventional machining processes. Laser Beam Machining (LBM) is an effective solution to these challenges due to its high precision, reduced heat-affected zone, non-contact process, versatility, and ability to integrate into automated manufacturing processes. Its performance is varied by adjusting laser power, beam diameter, pulse frequency, and beam focus, providing flexibility and precision tailored to specific machining requirements. The aim of this research is to compare the performance of CO_2 and fiber laser based machining, and to analyze the effect of input parameters viz. laser power, cutting speed and assist-gas pressure on the performance parameters such as surface roughness and kerf top. The variations in laser cut quality with respect to different process parameters are studied using Box- Behnken using response surface methodology (RSM) implementing design of experiment (DOE) software. The comparison of simulated data with actual data using artificial neural network (ANN) model showed better agreement for predicting the performance parameters with above 98% accuracy for the given set of input parameters data. From the comparison of laser cut quality obtained from CO_2 and fiber laser cutting machines, it is determined that CO_2 laser performs better than fiber laser for thicker materials.

Keywords: LBM; kerf; Surface Roughness (SR); CO_2 laser; Fiber laser; DOE; ANN

1 Introduction

Laser Beam Machining (LBM) is a non- conventional manufacturing process that uses a high-intensity laser beam to remove material from a workpiece. LBM offers several benefits over conventional machining techniques, including higher precision, faster machining speeds, and the ability to process a wide range of materials. The need for laser beam machining arises from the increasing demand for high-precision components in various industries, including aerospace, medical, and electronics. LBM provides a cost-effective solution for machining complex geometries and materials that are difficult to process using traditional machining techniques. The material used for the experiment in this study is Stainless Steel Grade 316L. Stainless Steel 316L, commonly abbreviated as SS316L, is a widely used austenitic stainless steel with a low carbon content, which provides excellent corrosion resistance and high-temperature strength. It is often used in harsh environments, such as marine and chemical processing industries, due to its resistance to corrosion and pitting. SS316L is a popular material for a wide range of applications, including medical implants, food processing equipment, and aerospace components, due to its high strength, good ductility, and excel- lent weldability. Its low carbon content makes it resistant to sensitization, a phenomenon that can occur when stainless steels are exposed to high temperatures, which can lead to corrosion and cracking. Ghazi et al. [1] utilized Taguchi-Grey Relation Analysis (TGRA) to determine the optimal process variables for LBM process that would result in a better material removal rate, better surface finish, and a smaller taper angle. Muthuramalingam et al. [2] used Taguchi-Grey relational approach to examine the effects of process parameters on surface performance measures during the machining of titanium alloy on a CO_2 based LBM. They found that laser power has the high influence on determining the quality measures on surface roughness and taper angle in LBM due its importance of plasma energy. Magdum et al. [3] focused on the likely application of LBM for machining a variety of materials, current progress, advantages and difficulties in machining, process parameters, performance characteristics, modeling and optimization. They stated that investigational based modeling and optimization methods are essential to generate model that gives very good fitting with experiments, while determining the effects of several process parameters. Geethapriyan et al. [4] investigated how process parameters affect machining of leather on CO_2 based laser cutting machine for use in an oil hydraulic system. The main input parameters (laser power, transverse speed, standoff distance and Gas pressure) were altered to achieve the optimal values for the response parameters (Material Removal Rate (MRR), Conicity, Overcut, and Circularity). The transverse speed was found to be the factor that had greatest impact on the MRR and circularity of the inner diameter entrance. Roy et al. [5] presented a comparative study on depth of cut during laser blind cut on Inconel 625 superalloy at different environment. They concluded that lamp current is the most significant process variable which is sensitive to depth of cut though the statistical contribution of the said parameter is not favorable. Mao et al. [6] presented a theoretical analysis and experimental validation of the mechanism of micropit surface texture formation in brass. They concluded that lasers can quickly produce a micropit surface texture and compressive stress is a significant mechanism of damage effect, thermal stress damage occurs first, followed by melting damage. Patel et al. [7] investigated on a CO_2 laser to cut hard die steel plate (EN-31, 10 mm thick) in order to determine the effects of processing parameters on taper angle, surface roughness (Ra), and Heat Affected Zone (HAZ). Anghel et al. [8] discussed on a single and multi performance optimization of LBM parameters for productivity and surface quality of miniature stainless steel gears. They used a statistical optimization technique, desirability analysis for optimization. Pramanik et al. [9]

investigated to determine the low power fiber laser's ability to cut stainless steel sheets with a thickness of 1 mm. Through the use of the RSM with Central Composite Design (CCD) technique, they evaluated the impact of the cutting wedge angle as well as other process variables such as power, duty cycle, pulse frequency, and scanning speed. They concluded that the effect of the cutting wedge angle on kerf taper is that when the wedge angle becomes greater the kerf width will be larger accordingly and due to this kerf taper will also appear. The kerf taper is influenced by all the process control parameters during laser beam cutting and optimization of input process parameters can support to attain high dimensional precision. Muthuramalingama et al. [10] analyzed the impacts of LBM process parameters while drilling holes through titanium (Ti-6Al-4V) alloy using the Taguchi technique. They concluded that power and gas pressure play a crucial role in determining the machining precision with the lowest power whereas power and nozzle distance play a critical role in determining accurate roundness. Sharma & Yadava [11] conducted an experimental analysis of the Nd-YAG laser cutting process to examine how the laser cutting parameters affect the process performance index. The researchers discovered that the laser parameters (laser power, wavelength, mode of operation), sheet material (type, thickness), and process parameters such as pulse width or duration, current, cutting speed, travel direction, pulse frequency, focal plane position, pulse energy, assist gas type and pressure are crucial input process characteristics that influence the laser cut quality.

In this study, two plates of SS316L are cut using CO_2 and Fiber based laser cutting machines for comparison and analysis of process and performance parameters. Laser power, cutting speed and assist gas pressure are the process parameters considered for the experimentation. Surface roughness and kerf top are the performance parameters that are analyzed. For the performance of the experiment, Box Behnken Design was implemented in response surface methodology (RSM) using design of experiment (DOE) software. Analysis of Variance (ANOVA) is carried out to find the relative influence of process parameters using DOE. An ANN model was developed to predict the performance and the statistical data was analyzed to determine the closeness of predicted values to the experimental data.

2 Experimental Methodology

2.1 Material Preparation

As shown in Fig. 1, two SS316L plates were used for the experiment. The size of each plate was: 200x300x18mm. 17 square blocks of size: 30x30mmis cut out of both plates.

Fig. 1: Plate machined on fiber laser

2.2 Experimental Setup

The machining of the samples was done in two different industries according to the availability of the equipment. Both machines were rated at 6000 W maximum power output in continuous mode. The focal length and nozzle distance being 190 mm and 2.5 mm respectively. The nozzle diameter for both machines was 1.4 mm. Two machines used in this research work are:

1. Amada LCG 3015 AJ (Fiber Laser)
   a. Location: Anand Lasers, Narhe, Pune
   b. Maximum power: 6000 W
   c. Assist gas type: Nitrogen and Oxygen

2. Trumpf TruLaser 6000 (CO_2 Laser)
   a. Location: Prime Lasers, Bhosari, Pimpri-Chinchwad
   b. Maximum power: 6000 W
   c. Assist gas type: Nitrogen and Oxygen

2.3 Experimental Parameters

In the experiment, there is a number of fixed and variable process parameters considered. The fixed parameters were focal length, nozzle diameter, nozzle tip distance and material thickness and the values are as mention in section 2.1 and 2.2 whereas the variable parameters were laser power, cutting speed and assist gas pressure. According to machine manufacturer recommendation for SS material, nitrogen was selected as the assist gas for both machines. The range of values for the variable parameters is determined as mentioned in the table 1. After entering the range of the parameters, as shown in table 1, in Box Behnken design of RSM in Design expert software, 17 different combinations of input parameters are obtained. These variations are shown in table 2.

Table 1: Range of input parameters

Parameter	Minimum	Maximum	Unit
Power	5.9	6	kw
Cutting speed	100	300	mm/min
Assist gas pressure	1.5	1.8	MPa

Table 2: Generated combinations of process parameters

Run	Power	Cutting Speed	Assist Gas Pressure
1	5.99	200	1.5
2	6	200	1.5
3	5.99	200	1.65
4	5.99	100	1.5
5	5.995	300	1.5
6	6	200	1.65
7	5.995	200	1.65
8	6	100	1.65
9	5.995	300	1.65
10	5.995	200	1.65
11	5.99	100	1.65

12	5.995	300	1.65
13	5.995	200	1.65
14	5.995	200	1.8
15	6	100	1.8
16	5.995	200	1.8
17	5.995	300	1.8

2.4 Measurement of performanceparameters

2.4.1 Measurement of surface roughness

The surface roughness of the cut was measured from the sides of the 30x30mm square blocks. Mitutoyo SJ-210 surftest portable surface roughness tester was used to obtain the values in microns. Three readings on each side of the blocks were taken and the average values were calculated. Fig. 2 shows the instrument that was used for measurement if surface roughness.

Fig. 2: Surface roughness tester

2.4.2 Measurement of kerf top

The measurement of kerf top (mm) was carried out on Tool Makers Microscope. Tool Makers microscope provides a high degree of magnification and is also a simple and convenient means for taking readings. Fig. 3 shows the instrument that was used for measurement of kerf top.

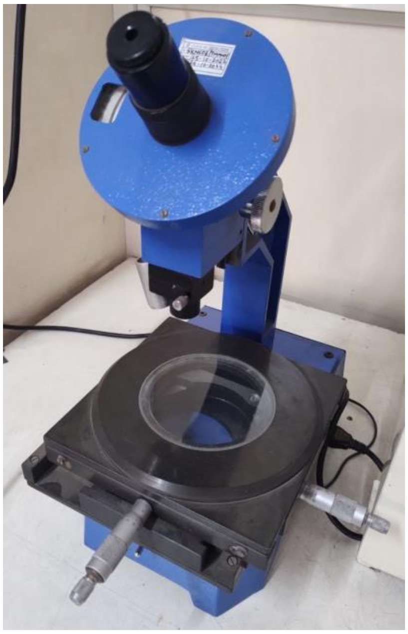

Fig. 3: Tool makers microscope

3 Various modeling techniques

3.1 ANOVA

3.1.1 CO_2 laser

ANOVA of surface roughness

The ANOVA results of surface roughness of cut are presented in the table 3. The p-values of cutting speed and gas pressure are less than 0.05 hence it is observed that the effect of cutting speed and gas pressure on surface roughness is significant. The p-values of power are greater than 0.05, reason being the lack of variation. Hence in this particular experiment, the significance of laser power will remain undetermined. The R-Sq value is obtained 99.22% which is very close to 100% which suggests that the response data fits well in the model.

ANOVA of kerf top

The ANOVA results of kerf top of cut are presented in the table 4. The p-values of cutting speed and gas pressure are less than 0.05 hence it can be determined that the effect of cutting speed and gas pressure on kerf top is significant. The p-values of power are greater than 0.05, reason being the lack of variation. Hence in this particular experiment, the significance of laser power will remain undetermined. The R-Sq value is obtained 99.34% which is very close to 100% which suggests that the response data fits well in the model.

3.1.2 Fiber laser

ANOVA of surface roughness

The ANOVA results of surface roughness of cut are presented in the table 5. The p-values of cutting speed and gas pressure are less than 0.05 hence it is determined that the effect of cutting speed and gas pressure on surface roughness is significant. The p-values of power are greater than 0.05, reason being the lack of variation. Hence in this particular experiment, the significance of laser power will remain undetermined. The R-Sq value is obtained 98.97% which is very close to 100% which suggests that the response data fits well in the model.

ANOVA of kerf top

The ANOVA results of kerf top of cut are presented in the table 6. The p-values of cutting speed and gas pressure are less than 0.05 hence it is determined that the effect of cutting speed and gas pressure on kerf top is significant. The p-values of power are greater than 0.05, reason being the lack of variation. Hence in this particular experiment, the significance of laser power will remain undetermined. The R-Sq value is obtained 99.21% which is very close to 100% which suggests that the response data fits well in the model.

Table 3: Results of ANOVA for surface roughness on CO_2 laser

Source	DF	Sum of Squares	f - value	p - value
Power	1	0.0018	0.4284	0.5337
Cutting Speed	1	1.08	252.13	<0.0001
Gas Pressure	1	0.2902	67.47	<0.0001

Error	13	0.0301		
Total	16	1.4021		
S = 0.0656	R-Sq = 99.22%	R-Sq(adj) = 98.23%		

Table 4: Results of ANOVA for kerf top on CO_2 laser

Source	DF	Sum of Squares	f - value	p - value
Power	1	0.0005	1.04	0.3409
Cutting Speed	1	0.1292	278.48	<0.0001
Gas Pressure	1	0.0436	93.89	<0.0001
Error	13	0.0032		
Total	16	0.1765		
S = 0.0215	R-Sq = 99.34%	R-Sq(adj) = 98.49%		

Table 5: Results of ANOVA for surface roughness on fiber laser

Source	DF	Sum of Squares	f - value	p - value
Power	1	0	0.0538	0.8233
Cutting Speed	1	0.3122	363.18	<0.0001
Gas Pressure	1	0.0803	93.45	<0.0001
Error	13	0.006		
Total	16	0.3985		
S = 0.0293	R-Sq = 98.97%	R-Sq(adj) = 97.64%		

Table 6: Results of ANOVA for kerf top on fiber laser

Source	DF	Sum of Squares	f - value	p - value
Power	1	0.0003	0.2714	0.6185
Cutting Speed	1	0.7544	597.18	<0.0001
Gas Pressure	1	0.0877	69.4	<0.0001
Error	13	0.0088		
Total	16	0.8512		
S = 0.0355	R-Sq = 99.21%	R-Sq(adj) = 98.20%		

3.2 ANN

An Artificial Neural Network (ANN) is a computational model inspired by the structure and function of the human brain. It is a type of machine learning algorithm that is used to recognize complex patterns and relationships in large data sets. The basic building block of an ANN is a neuron, which receives inputs, applies a weight to each input, and then applies an activation function to the weighted sum of the inputs. The output of the activation function is then sent to other neurons in the network.

An ANN typically consists of multiple layers of neurons, with each layer performing a specific function in the overall computation. The first layer, known as the input layer, receives the input data, and subsequent layers, known as hidden layers, perform increasingly complex computations on the data. The final layer, known as the output layer, produces the final output of the network. Fig. 4 shows a schematic artificial neural network.

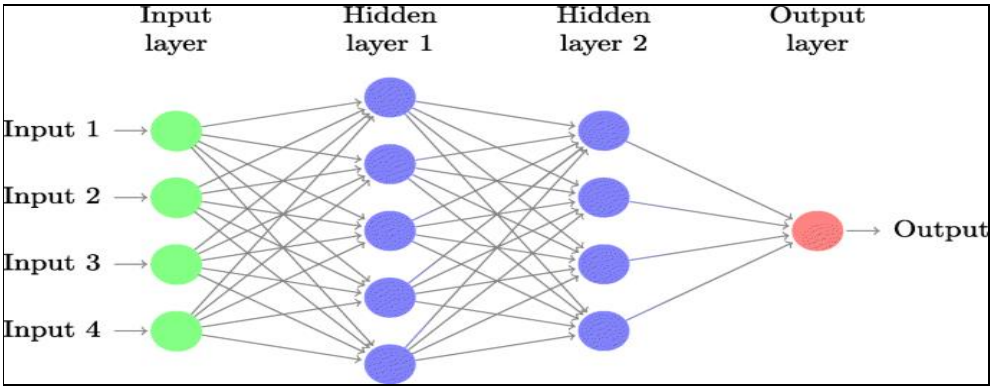

Fig. 4: Artificial neural network [12]

After training the ANN model on Matlab software, we obtained the values of mean square error and regression. The obtained values are shown in table 7.

As it can be seen in table 7, the values of mean square error are close to 0 and the values of regression are closer to 1, this proves there is a close relationship between the predicted and actual outcomes.

Table 7: ANN results

Value	Mean square error	Regression			
		Training	Validation	Test	All
CO_2 laser	0.0067705	0.99994	0.99984	0.97203	0.9886
Fiber laser	0.071526	0.99994	0.99702	0.99136	0.99777

4 Comparison of results

Table 8 shows the comparison between the performance parameters of CO_2 and fiber laser. It is noted that CO_2 laser provides better surface finish and smaller kerf top width.

Table 8: Comparison of performance parameters

Run No.	Power kW	Cutting Speed mm/min	Gas Pressure µm	Surface Roughness µm		Kerf Top mm	
				CO_2	Fiber	CO_2	Fiber
1	5.99	200	1.5	2.84	4.59737	0.73	1.43
2	6	200	1.5	2.79133	4.63297	0.7	1.42
3	5.99	200	1.65	2.70567	4.52769	0.68	1.35
4	5.99	100	1.5	2.42	4.31172	0.97	1.8
5	5.995	300	1.5	3.88267	4.75455	0.47	1.11
6	6	200	1.65	2.68867	4.4943	0.65	1.34
7	5.995	200	1.65	2.71367	4.47361	0.63	1.3
8	6	100	1.65	2.27633	4.15833	0.93	1.68
9	5.995	300	1.65	3.585	4.63718	0.45	1.01
10	5.995	200	1.65	2.69833	4.45289	0.6	1.29
11	5.99	100	1.65	2.351	4.1745	0.83	1.65
12	5.995	300	1.65	3.44567	4.60478	0.43	0.91
13	5.995	200	1.65	2.674	4.50644	0.59	1.28
14	5.995	200	1.8	2.467	4.33747	0.52	1.16
15	6	100	1.8	1.96733	4.07725	0.75	1.46
16	5.995	200	1.8	2.43233	4.32324	0.5	1.12
17	5.995	300	1.8	3.07733	4.57909	0.34	0.83

Fig. 5 represents the comparison between surface roughness of CO_2 and fiber laser. It shows that the surface roughness is better in CO_2 compared to fiber laser.

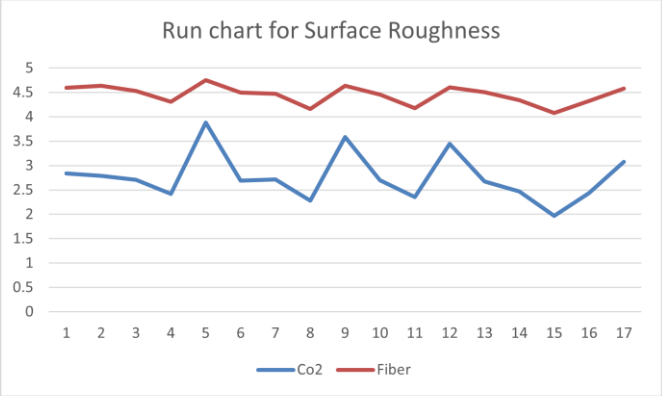

Fig. 5: Run chart for surface roughness

Fig. 6 represents the comparison between kerf top of CO_2 and fiber laser. It shows that the kerf top is smaller in CO_2 compared to fiber laser.

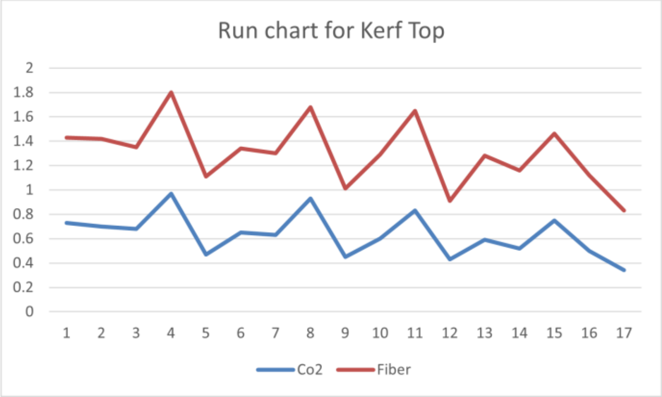

Fig. 6: Run chart for kerf top

5 Conclusion

The proposed work is focused on Comparative study of CO_2 and Fiber LBM on SS316L and optimization of parameters on ANN using Matlab. The aim was to determine the type of laser that provides best surface finish for the selected conditions. Among the three input parameters, cutting speed turned out to be most significant parameterwhen laser power variation is near constant.

It is concluded that:

•Increase in cutting speed increases surface roughness.

•Surface finish obtained in CO_2 laser is better than that of Fiber laser. The best surface finish obtained in CO_2 was 1.86733 µm whereas Fiber laser produced surface roughness of 4.07725 µm at same parameters

•Kerf top width is smaller in CO_2 laser.

•From all output responses, it is observed that best surface finish is obtained at high power and high assist gas pressure with low cutting speed.

6 Future Scope

Laser beam machining (LBM) is a constantly evolving technology, and its future scope is promising. Some of the potential areas for research in LBM include:

•Parameter optimization using new advance algorithms such as Fuzzy logic algorithms.

•Comparison of LBM with other advance machining processes such as water jet machining (WJM), abrasive-WJM (AWJM), plasma arc machining (PAM), etc.

•Investigate the feasibility and effectiveness of laser cutting for new materials, such as advanced composites and additive manufacturing materials, to expand the application range of laser cutting.

•Application of LBM in surface modification of materials such as surface texturing, surface hardening, and surface coating.

References

[1] Ghazi Alsoruji; T. Muthuramalingam; Essam B. Moustafa; Ammar Elsheikh. Investigation and TGRA based optimization of laser beam drilling process during machining of Nickel Inconel 718 alloy. *Journal of Materials Research and Technology* **2022**, *18*, 720–730.

[2] T. Muthuramalingam; Ravi Akash; Shravan Krishnan; Nguyen Huu Phan; Vu Ngoc Pi; Ammar H. Elsheikh. Surface quality measures analysis and optimization on machining titanium alloy using CO_2 based laser beam drilling process. *Journal of Manufacturing Processes* **2021**, *62*, 1–6.

[3] V. B. Magdum; J. K. Kittur. A review on laser beam machining process modeling and optimization. *IOP Conference Series: Materials Science and Engineering* **2021**, *1104*, 012015.

[4] T. Geethapriyan; A. C. Arun Raj; T. Deepan Bharathi Kannan; S. Senkathir. Influence of process parameters on laser beam machining of leather for oil hydraulic system application. *Materials Today: Proceedings* **2021**, *47*, 4508–4512, International Conference on Futuristic Research in Engineering Smart Materials (FRESM'21).

[5] N. Roy; D. Pramanik; A. S. Kuar. Comparative study on quality characteristic of pulsed laser beam cutting of Inconel 625 superalloy at different environment by sensitivity analysis. Optik 2021, 232, 166516.

[6] Ya-Zhou Mao; Jian-Xi Yang; Jin-Chen Ji. Theoretical and experimental study of surface texturing with laser machining. Advances in Manufacturing 2021, 9, 538–557.

[7] Amit Patel; Sanket N. Bhavsar. Experimental investigation to optimize laser cutting process parameters for difficult to cut die alloy steel using response surface methodology. Materials Today: Proceedings 2021, 43, 28–35, 1st International Conference on Energy, Material Sciences and Mechanical Engineering.

[8] C. Anghel; K. Gupta; T. C. Jen. Optimization of Laser Machining Parameters and Surface Integrity Analysis of the Fabricated Miniature Gears. Procedia Manufacturing 2020, 51, 878–884, 30th International Conference on Flexible Automation and Intelligent Manufacturing (FAIM2021).

[9] D. Pramanik; A.S Kuar; S. Sarkar; S. Mitra. Optimisation of edge quality on stainless steel 316L using low power fiber laser beam machining. Advances in Materials and Processing Technologies 2021, 7, 42–53.

[10] T. Muthuramalingam; Khaja Moiduddin; Ravi Akash; Shravan Krishnan; Syed Hammad Mian; Wadea Ameen; Hisham Alkhalefah, Influence of process parameters on dimensional accuracy of machined Titanium (Ti-6Al-4V) alloy in Laser Beam Machining Process. Optics & Laser Technology 2020, 132, 106494.

[11] Sharma A.; Yadava V. Experimental analysis of Nd-YAG laser cutting of sheet materials – A review. Optics & Laser Technology 2018, 98, 264–280.

[12] Holmgren G.; Andersson P.; Jakobsson A. et al. Artificial neural networks improve and simplify intensive care mortality prognostication: a national cohort study of 217,289 first-time intensive care unit admissions. j intensive care 7(1), 44 (2019). https://doi.org/10.1186/s40560-019-0393-1.