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Scope and topics

Advances in Production Engineering & Management (*APEM journal*) is an interdisciplinary refereed international academic journal published quarterly by the *Production Engineering Institute* at the *University of Maribor*. The main goal of the *APEM journal* is to present original, high quality, theoretical and application-oriented research developments in all areas of production engineering and production management to a broad audience of academics and practitioners. In order to bridge the gap between theory and practice, applications based on advanced theory and case studies are particularly welcome. For theoretical papers, their originality and research contributions are the main factors in the evaluation process. General approaches, formalisms, algorithms or techniques should be illustrated with significant applications that demonstrate their applicability to real-world problems. Although the *APEM journal* main goal is to publish original research papers, review articles and professional papers are occasionally published.

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Original scientific paper

Lean capacity planning for tool room: An iterative system improvement approach

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ABSTRACT

Capacity planning helps to synchronize demands and production volumes, and assists in early preparedness for dealing with future production imbalances. A tool room of armored manufacturing organization was selected for this work study. Initially, a master production schedule and rough cut capacity plans are prepared based on the delivery commitments of the organization. Time and motion study of the tool room for 28 weeks was performed to determine its current production capacity. It was observed that imbalance between demands and production exists. An iterative system improvement strategy was proposed for exploring the potential of tool room. Lean concepts and methodologies were the essence of the proposed system improvement strategy. It was observed that WIP had been reduced by 18 %, production volumes had improved by 24 % and tardiness reduced by 28 %. This strengthened our belief that lean philosophy is equally applicable within the capacity planning domain. The capacity planning approach presented in this work study could also be generalized for other domains. This approach believes in improving the potential through elimination of wastes, process improvement, defect prevention and total preventative maintenance. This approach improves the system optimally by utilizing existing resources available on the shop floor. This research will be further expanded towards the major production units of this organization. We are currently working on capacity planning for rebuilding the activities of T-80 UD battlefield tanks.

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1. Introduction

Capacity planning helps organizations to know their capabilities to produce. Organizations can respond to forthcoming production forecasts by exploiting this potential and maintaining desired rate of production. This proactive response can manage production imbalances and succeeds in retaining existing customers. A transparent and smooth production flow owing to customer demands can help plan for expansion in business. Management can optimally assign resources and reduce costs incurred on carrying unnecessary inventories. Organizations make sensible commitments and systematically move forward with their customers. Furthermore, this helps organizations to design suitable facility layouts that can guarantee higher productivity and minimal costs. Capacity planning is dependent upon proper evaluation of certain input factors that may include raw material, plant downtime, inventory, workforce and market share [1].

Granularity of understanding can be improved by decomposition of capacity planning process. Initial level (0-level) performs resource planning for organization. At 0-level, key resources are defined to determine appropriate layout required for organization. Furthermore, infrastructure and logistics requirement is established. Level-1 plans within the facility and determines requirements of workstations suitable for production activity. An estimated capacity from these workstations can be calculated based on available workstations and process flow. Level-2 decomposition identifies execution plans, how to monitor and control production activity. This level of decomposition determines inputs and output at shop floor. It is common practice to define three level of capacity planning [2]. In an existing facility, capacity planning can be implemented through re-engineering. A re-engineering process for an existing facility will adopt bottom up strategy and will be reverse capacity planning activity [1, 3].

Mostly, organizations believe in 'make to order strategy' to produce desired production volumes. Fluctuations in demand may arise under certain circumstances. Such abrupt increases or decreases in demand will result in failure to meet customer demands. This situation will result in failure of 'make to order' strategy. Whenever, there exists possibilities that abrupt changes in demands may occur, organizations follow contingency plan by adopting lead or lag strategies for capacity planning. None of these strategies can be trusted altogether and each has its own prospects and consequences. Any increase in demand can be fulfilled by 'production in advance'. This strategy will help in winning confidence of customers through timely delivery of product. 'Production in advance' will require extra space for additional products to store. In worst case situation, an abrupt drop in demand will cause salvage of overproduced products. Inventory carrying cost and wastage due to overproduction are two major drawbacks of lead or production in advance strategy. With 'delayed production', possibilities of drops in demand can be managed. In case of sudden escalation of demands, this strategy will not be able to fulfil customer demands and will subsequently result in losing the confidence of customers. Preferably, each organization must have its own customized capacity planning strategy exploiting blend of more than one strategy. Make to order strategy is suitable for low volume production activity and "lead" can be adopted for higher volume production. It is common practice that organizations run at lower than designed rates of production due to real life constraints and production losses [1-4].

In an existing facility, capacity planning can be implemented through re-engineering. A re-engineering process for an existing facility will adopt bottom up strategy and will be "reverse capacity planning" activity. Existing and proposed organizational setups can be modelled to support capacity planning process. Proposed organizational setups result from implementation of capacity planning strategies e.g. value stream map in lean capacity planning process. Lean philosophy was implemented in capacity planning domain by Linne and Ekhall [3]. Authors proposed methodology to identify problems in capacity planning process and resolution of these problems through lean. Their work supported high level implementation of lean in capacity planning process. Their proposed solution can be taken as Pre-Capacity Planning Process lean implementation. It is useful to implement lean more rigorously during capacity planning process. An amalgam of lean and capacity planning process may result in cost effective capacity enhancement.

This research work proposes bottom up lean capacity planning strategy for an existing organizational setup. An integrated implementation of lean and capacity planning during re-engineering activity is presented. In this model, each level of capacity planning is given "lean attention". Initially, lean is implemented at level-2 and its prospects improve level-1. Lean implementation at level-1 improves capacity planning process at 0-level. Proposed model will provide better solution for effective capacity planning.

Remainder of the paper is organized as follows. Related work is outlined in Section 2. In section 3, we have briefly identified the problems being faced by tool room. Section 4, is about the capacity planning initiative taken in this research to study the existing capacity and future demands for tool room. Proposed capacity planning approach has been described in Section 5. In order to validate the suitability of proposed approach, performance measures have been discussed in section 6. We have briefly discussed our experimental study in Section 7. Results are discussed in section 8 and reviewed and analyzed in Section 9. Section 10 is the last but not the least and concludes our research work and gives future directions.

2. Related work

It is possible to identify issues and their root causes associated with a capacity planning process. Panacea to these issues can be found in lean principles [3]. These lean principles can be implemented in a capacity planning process. Based on this implementation, an improved model for capacity planning can be presented. This is high level application of lean in capacity planning process. Decomposition of capacity planning process allows implementation of lean principles and tools at lower levels. Introducing lean capacity planning process is preferable than implementing lean principles only on identified problem areas [3]. Production activities can be modelled using value stream maps (VSM) [5].Furthermore, it is possible to analyse and review value stream maps and identify potential improvements. Well worked value stream maps can be used to identify starving, saturated and bottleneck stations. Simulation models can replace value stream maps to validate suggested improvements. Complimentary use of value stream map and simulation model can be suggested. Proactive and reactive lean logistics for resource planning phase of capacity planning are suggested using value stream map and identification of bottleneck resources [5]. Capacity planning has also been extensively studied in service sector apart from manufacturing sector e.g. emergency departments of hospitals [6-7]. Long waiting times in queue affect provisioning of service to patients in hospital. Value stream mapping of current scenario can be used to identify root causes of long queues. Simulation model identified flaws in current resource planning with identification of possible improvements. These improvements can be iteratively used to identify suitable solution [8]. Alternate solutions achieved through iterative improvements provide flexibility to adopt suitable solution for enhanced capacity planning. This approach was implemented in automotive sector of Thailand using Tecnomatrix software. Re-engineering the facility and inclusion of further resources to enhance capacity for escalated demands was achieved through simulation of fabrication shop models [9]. Identification of saturated and starved resources helped reduce workers and adjustment of arrival and indexed times for conveyors. This was also helpful to propose better layout and facility design. Similarly, excessive transportation and undesired motion of workforce can also be addressed through value stream mapping [10].

Apart from value stream mapping, other lean methodologies like 5S, Meiruka and Kaizan helped propose “to-be” model from “as-is” model [11]. Regression analysis conducted on these methodologies determined the effectiveness of these methodologies. “Tam the” model improved the effectiveness of lean capacity planning process. This research study believes in utilizing bottom up lean methodology in capacity planning.

Reviewed literature shows that existing initiatives partially implement lean philosophy in capacity planning. Lean capacity requirement planning can improve rough cut capacity plans and subsequently lean rough cut capacity plans can be used for better resource planning. Existing research is focused on lean resource planning and ignores lean capacity requirement planning and lean rough cut capacity plans.

3. Problem statement

Precision Defense Organization (PDO) is a strategic organization and is rebuilding and manufacturing armored vehicles of Chinese, Russian and American origin. It has five major units for manufacturing and rebuilding of battlefield tanks, gun barrels, armored personnel carriers and self-propelled guns.These units have assembling, heattreatment, machining and fabrication shops. Manufacturing and rebuild of armored vehicles demands rigorous machining operations with special purpose tooling, jigs and fixtures. Special purpose tooling is required for complex and specific machining tasks e.g. machine gun holes etc.Tool manufacturing shop also known as tool room is primarily responsible to provide standard and special purpose tooling to these units. PDO believes in indigenous production of armored vehicles and discourages import of tooling, jigs and fixtures from abroad.

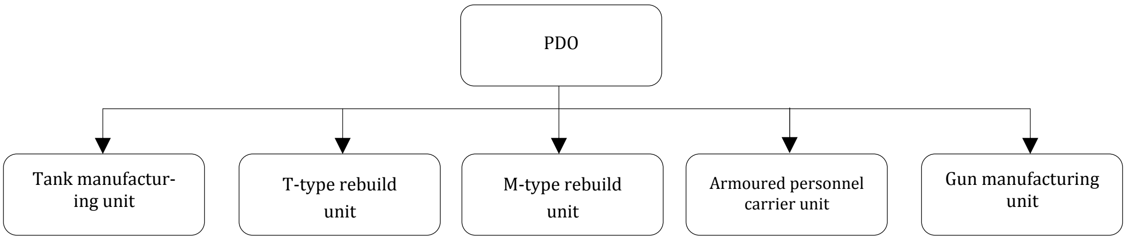

Fig. 1 Manufacturing units of PDO

Senior management decides production targets keeping in view the strategic position of customer. Suppose a strategic decision is made to upgrade fleet of 500old t-type battlefield tanks.Customer demands completion of this task in five years. Senior management has no option other than upgrading 10 battlefield tanks in a month. This results in unwanted burden on major and supporting units.PDO has a team of experts who prepares master production schedules, rough cut capacity plans and bill of materials for these targets.This team prepares detailed demand of tooling, jigs and fixtures for tool room supervisors.Due to technical and managerial constraints, tool room suffers failure to manufacture demanded quantity of tooling.Some of the work orders are returned without any action due to heavy workload on machining facility of tool room.Special purpose tooling e.g. corn mill cutters and long shank drills are not available in local market.

There exist two alternatives to resolve this problem.Initially, PDO units seek help of local vendors for procurement of these tools.Inability of local vendors to provide special purpose tooling forces import of these tools from brotherly country, China.Import of these tooling is expensive and time consuming activity.Long lead times of these tooling hamper the production activity and non-availability of tooling on time results in delayed production of final products.Customer keeps on sending armored vehicles according to promised schedules. Strategic assets get strangled at PDO with large work in process inventory and holds up. Held up vehicles, suffer wear and tear due to harsh weather as these wait for their turn.This results in weak strategic position of customer on its borders.

Senior management of PDO is more interested to provide viable delivery targets to its customer. These viable targets can be set after detailed analysis of existing system and proper capacity planning. This study is aimed to provide solid foundations for capacity planning of tool room.

4. Capacity planning initiative

Three basic steps of capacity planning include determination of capacity requirements, evaluation of existing capacity and prepare future plan to meet the capacity requirements [12]. Our initial response towards this problem was to prepare Master Production Schedule (MPS) and perform rough cut capacity planning for tool room [13-14].An initial MPS for PDO is given in Table 1. Production targets for each unit are set by top management after high level meeting with representative group of customer.

After inquisitive meetings with production managers of manufacturing units, MPS for tool room was prepared (Table 2). This MPS contains desired quantities for critical tools in next 8 weeks. It was observed that tool room has to constantly feed major units and any slackness may bring miseries for tool room and PDO. Some of these tooling have complicated machining processes and require skilled workforce e.g. corn cutter, module cutter.

Table 1 Monthly production volumes of vehicles at PDO

Vehicles	T-90 manufacturing	T-59 upgrade	M1-113 rebuild	M1-113 manufacturing	Gun barrel manufacturing
MSP	15	10	5	5	25

Table 2 MPS for tool room

Part	W1	W 2	W 3	W 4	W 5	W 6	W 7	W 8
Corn cutter	4	3	4	3	4	3	4	3
Side and face cutter	4	3	4	3	4	3	4	3
Module cutter	4	3	4	3	4	3	4	3
End mill cutter	4	3	4	3	4	3	4	3
Reamers	6	6	6	6	6	6	6	6
Drills	6	6	6	6	6	6	6	6
Miscellaneous shafts	6	6	6	6	6	6	6	6
Gears	5	6	5	6	5	6	5	6
MPS	**39**	**36**	**39**	**36**	**39**	**36**	**39**	**36**

Table 3 Typical MPS for corn cutter

Week	1	2	3	4	5	6	7	8
Forecast	3	2	2	3	3	2	2	3
Projected available	0	2	1	1	0	2	1	1
MPS	**0**	**4**	**3**	**4**	**3**	**4**	**3**	**4**

We prepared MPS for each tooling and then individual MPS were summed up to make MPS for tool room. A typical MPS record for corn mill cutter is given in Table 3.It was supposed that there exists a beginning inventory of three corn cutters in tool room.

Our next step was to prepare rough cut capacity plan for tool room. Planning factor (α) for work centresisdefined in Eq. 1. We performed time and motion study of tool room for consecutive eight weeks.We observed sequence of processes, set up times, processing times, wait times, arrival times, man hours spent and idle times.

$$\text{Planning factor}_{\text{work centre (wc)}} = \frac{Processing\ \ per\ part}{total\ parts\ produced} \tag{1}$$

We calculated total machining hours required for scheduled production of each part in tool room using Eq.2.

$$Work\ centre\ Time = Target\ Qty \times Planning\ Factor \tag{2}$$

Based on this time and motion study, processing times, parts produced, planning factor and machine hours for each part are given in Table 4.

Table 4 Rough cut capacity planning for tool room

Part	Processing [h]	Parts produced [qty]	Planning factor [wc]	Target [qty]	Machining [h]
Corn cutter	1481.8	2.3	10.52	4	42.06
Side and face cutter	1362.5	2.5	8.89	4	35.56
Module cutter	1249.3	2.7	7.47	4	29.90
End mill cutter	861.52	4	3.55	4	14.22
Reamers	481.86	7	1.11	6	6.67
Drills	703	5	2.37	6	14.20
Miscellaneous shafts	405.73	8.5	0.79	6	4.73
Gears	1105.7	3.14	5.86	5	29.28

We determined percentage of processing time spent on manufacturing processes for each tooling using Eq. 3 and is given in Table 5.

$$Percentage\ processing\ time = \frac{Workcentre\ time}{Total\ processing\ time} \times 100 \tag{3}$$

Table 5 Percentage of processing time for tool production

Part	Heat treatment	Turning	Milling	Grinding	Other
Corn cutter	20	20	35	20	5
Side and face cutter	15	25	45	15	0
Module cutter	15	20	40	20	5
End mill cutter	15	25	45	15	15
Reamers	10	25	50	10	5
Drills	10	25	50	10	5
Miscellaneous shafts	5	70	20	5	0
Gears	10	20	60	5	5

Processing time required for each manufacturing process to produce desired quantity of tooling in a week time is determined using Eq.4 and is given in Table 6.

$$Processing\ time = Percentage\ Processing\ Time \times Workcentre\ hrs \tag{4}$$

Table 6 Processing time for tool production (h)

Part	Heat treatment	Turning	Milling	Grinding	Other
Corn cutter	8.41	8.41	14.72	8.41	2.10
Side and face cutter	5.33	8.89	16.00	5.33	0.00
Module cutter	4.49	5.98	11.96	5.98	1.50
End mill cutter	2.13	3.56	6.40	2.13	2.13
Reamers	0.67	1.67	3.34	0.67	0.33
Drills	1.42	3.55	7.10	1.42	0.71
Miscellaneous shafts	0.24	3.31	0.95	0.24	0.00
Gears	2.93	5.86	17.57	1.46	1.46

It is true that capacity plan and MPS helped to understand the demand of customer and identified the shortcomings of the existing system. An important step in capacity planning was to determine whether the tool room is capable to work according to MPS and rough cut capacity plan. Research analysis of existing system performed over 8 weeks, necessitated process improvement to fulfil targeted deliveries reflected in MPS.

In order to exploit the potential of tool room and synchronize demand and production, it was decided to model the existing system and identify grey areas hampering production capability of the existing system.

5. Proposed capacity planning approach

This research identified the production gap existing between the desired and produced quantities of tooling (Fig. 2). It shows that all tooling is suffering under production except end mill cutters, reamers and shafts (Table 4). It is important to mention here that most of the gears are used in different machine tools. An inability to replace these gears in machine tools due to non-availability may affect production of end mill cutters, reamers and shafts as well. Corn cutters and side and face cutters are used in initial machining phase of turrets and hull assemblies of battlefield tanks and armoured personnel carriers.

Ideally, it was possible to modify the MPS of PDO based on production feasibility analysis of tool room (Fig. 3). Unfortunately, there was no two ways communication between PDO and tool room and PDO management was imposing production targets on tool room.

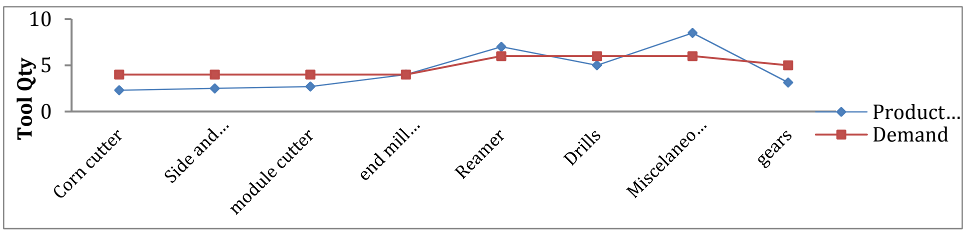

Fig. 2 Manufacturing units of PDO

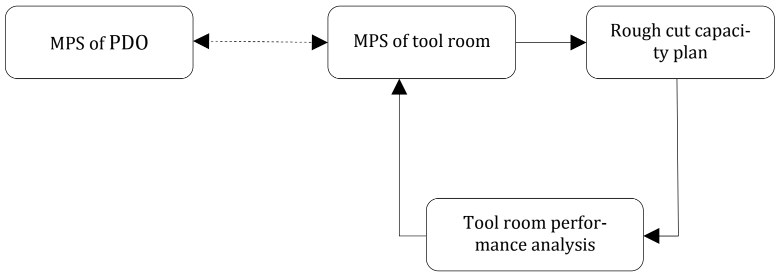

Fig. 3 Ideal capacity planning strategy

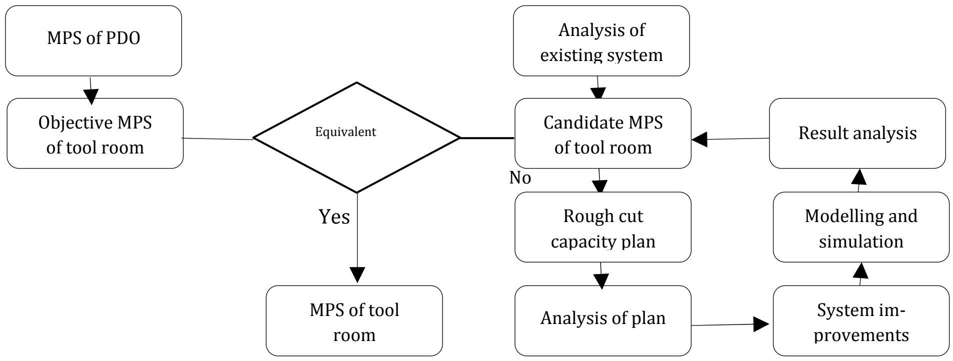

Fig. 4 Proposed capacity planning strategy

Our proposed iterative improvement strategy to tune demands and production is shown in Fig.4. This proposed approach was developed on motivation from genetic algorithms and computational intelligence domain [15].

Objective and candidate MPS are prepared using MPS of PDO and analysis of existing system respectively.If objective and candidate MPS of tool room are equivalent, candidate MPS becomes final MPS for tool room. In case of non-equivalence, iterative strategy for process improvement is implemented. A rough cut capacity plan is prepared using candidate MPS of tool room and is thoroughly reviewed for system and process improvements. Improved system is modelled and simulated for preparation of refined and improved candidate MPS of tool room. These steps are repeated for iterative improvement until objective and candidate MPS are equivalent. Although our proposed approach is specific to capacity planning of PDO tool room, yet it can also be equally used in other domains.

In proposed approach, we have used lean thinking for system improvement. Lean principles used in our approach for continuous improvement are given in Fig. 5.

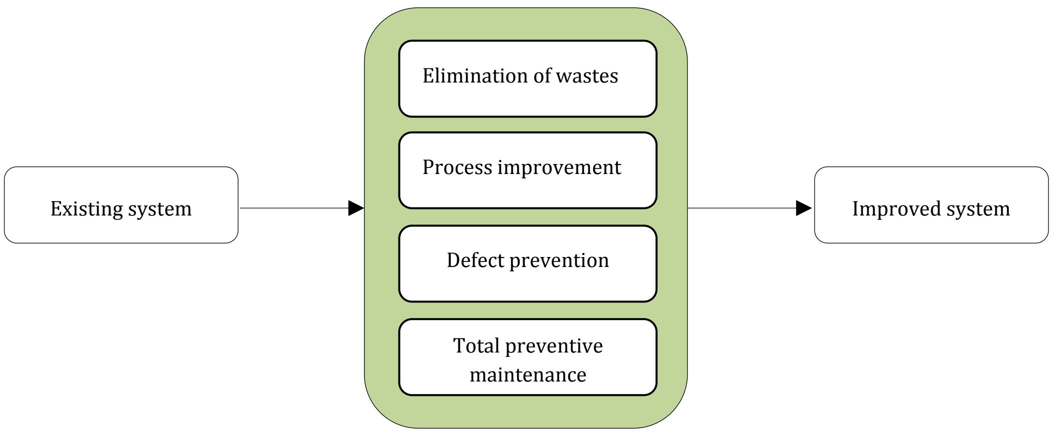

Fig. 5 Lean methodologies for system improvement

6. Performance measures and evaluation criteria

Performance measures to evaluate the usefulness of peoposed approach are defined as:

- Production volumes
- Work in process (WIP) inventory
- Mean flow times
- Mean tardiness
- Mean queue times

6.1 Production volumes

Productivity of a system is called its throughput and is gauged by the production volumes of the system.Objectively, production volumes of a system must match the demanded quantities.

6.2 Work in process (WIP)

Unfinished parts present in a system for value addition are termed as work in process (WIP) inventory[11]. Lower WIP inventory is an indication of efficient system. Preferably, WIP should be equal to the number of work cenres in the system.Thus WIP can never be lower than the number of work centres. If $WIP > \#\, Work\ centres$ then system is in saturation state else if $WIP < \#\, Work\ centres$ then system is in starvation state.

6.3 Mean flow times

It is the time spent by a part as WIP in the system and is also known as time in process (TIP) or process time [17-18]. Less mean flow times can be helpful to reduce WIP and improve production capacity of a manufacturing setup.

6.4 Mean tardiness

Any lateness in delivering the targeted production is termed as tardiness. Tardiness shows an inefficiency of the system and is discouraged by production managers. Ideally, there should be zero tardiness in delivering the targeted production volumes.

6.5 Mean queue times

It is total waiting time spent by a part in queues before some value addition at work centres. When WIP is equal to number of workstations, mean queue time is zero.

7. Experimental study

Our research encompasses 28 weeks time and motion study of tool room. Initial three steps of our proposed approach that inlcude preparation of candidate MPS, rough cut capacity plan and system analysis have already been performed in sections 3 and 4.Our next step in proposed methodolgy is to improve the system. It was discussed in section 4 that we have used lean thinking for system improvement. These proposed lean improvents are discussed as under;

7.1 Elimination of wastes

Lean identifies seven types of wastes in production systems. Elimination of these wastes helps to reduce flow times of parts produced.Some wastes found in tool room were due to poor layout and facility design. These wastes include undue transportation of tools and movement of work force. Other wastes in tool room include improper utilization of resources and long wait times before value addition.

This work addressed these wastes through re-arrangment of workcentres after generation of part families and making of cells (Table 7). Inorder to optimize resource utilization and reduce wait times, one piece flow strategy was implemented.

Table 7 Identification of part families [16]

Serial No	Part Family	Parts
1	Cutter family	Side and face cutter, Hobbing cutter, Corn mill cutter, End mill cutter, Slit saw cutter, module cutter
2	Reamer & drill family	Taper drill, Twist shank drill, Reamers
3	Gear family	Worm, Bevel, Spur gears
4	Lathe tool family	Right, left turning tool, parting tool, grooving tool, universal turning tool, 3&4 Jaw chucks
5	Gauge family	Ring, Snap, Plug gauges
6	Jigs and fixture family	Fixtures

7.2 Process improvement

Kaizan highlighted that system must be evoloved through continuous improvement.Our first initiative was to ensure quick changeover of tooling by inclusion of automatic tool changers on machines. We also identified starving and saturated stations and enhanced bottleneck workcentres in number and improved value added manhours. Improvement in value added manhours was achieved through reduction in breakdown time and mean time to failure. This was achieved by ensuring the availability of inventory for frequently wearing and tearing parts of machine tools.[20]

Arrival time of parts to the tool room from heat treatment shop was adjusted using input analyzer of Arena 10.0 and using poisson distribution. These requirements were communicated to manager of heat treatment shop for adherence.

7.3 Defect prevention

Production of defect free tooling is very important to meet delivery targets.Most of the parts in tool room were being rejected due to variations in heat treatment aspect of cutters.Unnecessary annealing and hardening made machining processes impossible on some parts. We suggested preparation of process sheets, inspection manuals and quality assurance for heat treatment process to prevent scrapping of tooling after hardening and annealing processes.

Secondly, we suggested improvements in programming blocks of numeric controlled machines to avoid manual errors caused by operators.

7.4 Total preventive maintenance

We observed long breakdown times for some work centres especially gear lathe and universal grinding machines due to non-availability of different machine tool parts.As discussed earlier, we have ensured that breakdown time is minimized through preventive maintenance and availability of frequently wearing out parts in inventory.

We modelled and simulated the improved system using Arena 10.0. Experimental results are discussed in Section 8.

8. Experimental results

Results obtained after simulation of improved system were analysed and reviewed with focus on predefined performance measures [19]. These findings are discussed as under;

8.1 Production volumes

Capacity planning is used to improve the existing production volumes of an industry and synchronize production with demands such that imbalances does not occur.It is observed that capacity of tool room has improved after lean based system improvements. Proposed approach has been successful to meet the demands for next 28 weeks except for gears (Fig. 6).

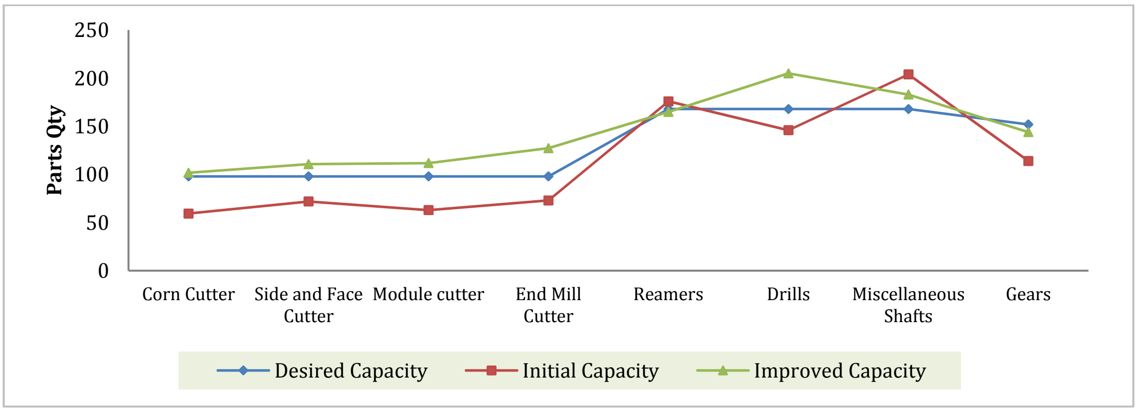

Fig. 6 Lean capacity planning of pool room

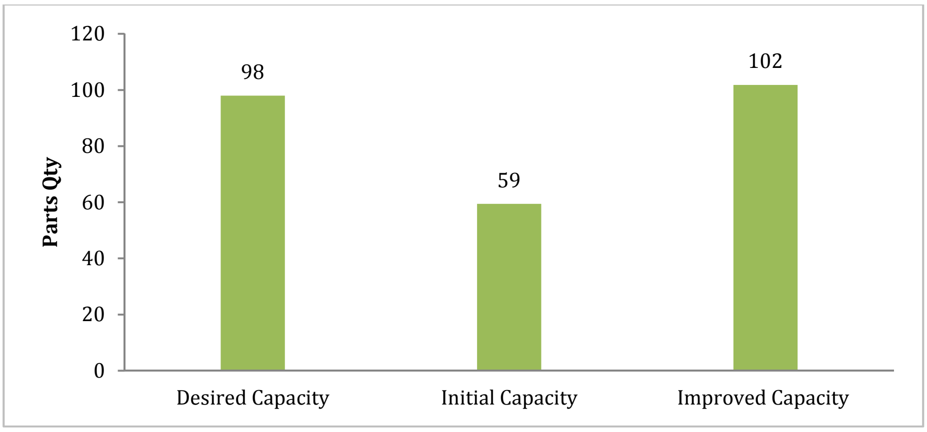

Fig. 7 Production volumes of corn mill cutter

Tool room management can seek alternatives to acquire or produce 8 deficient gears for machine tools. We have considered corn mill cutters and gears for detailed description of the proposed approach.

Corn mill cutters are used to machine trunions of gun mount assemblies on turrets in battlefield tanks. Initial candidated MPS reflects that existing tool room can produce upto 61 corn cutters in 28 weeks. Whereas objective MPS desires a production of 98 corn cutters. Proposed approach was successful to increase the production of corn cutters to an optimal level of 10 (Fig. 7).

Initial production of corn cutters was 60 % of the desired production volumes. Its detailed production for 28 weeks is shown in Fig. 8. In addition to lower weekly production, missing production weeks 16, 20 and 25 are also observed.

Most of the machine tools in PDO are conventional and require frequent repair. Gears are used for repair of these machine tools.Bevel, spur and worm gears are manufactured in tool room with quantity of 2 for each gear. Existing system was producing 114 gears with big flactuations of quantities each week (Fig. 9 and Fig. 10). System improvement resulted in 144 gears with almost smooth quantites each week.

These gears do not require longer times for surface treatment and are wholy solely managed by tool room. We can see better performance of tool room in production of these gears. Secondly, these gears do not require special machining processes except indexing on milling machines.

We have given a brief comparison of initial and improved production volumes in Table 8. These results show that room for further improvement in tool room still exists.

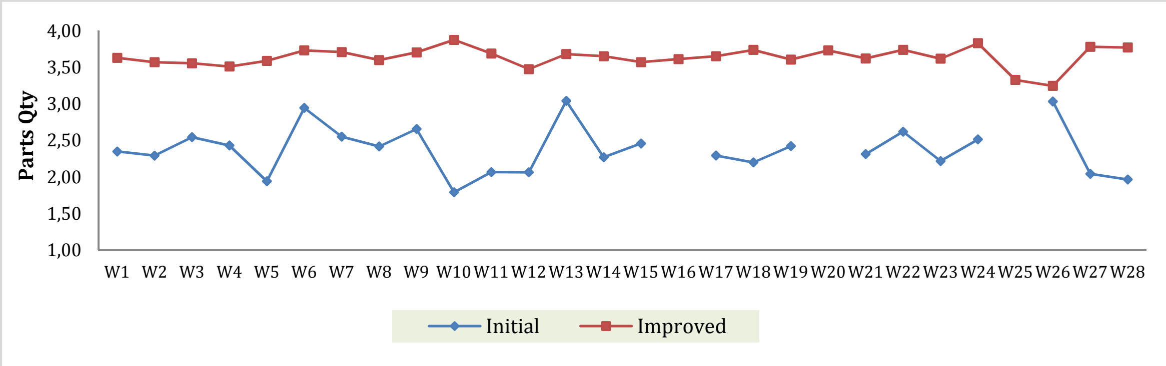

Fig. 8 Production volumes of corn mill cutter

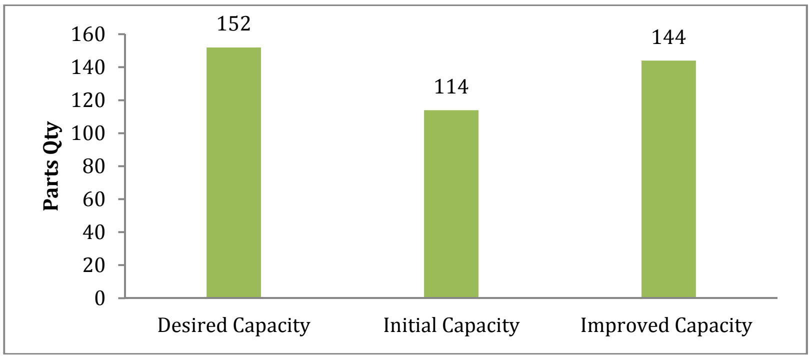

Fig. 9 Production volumes of gears

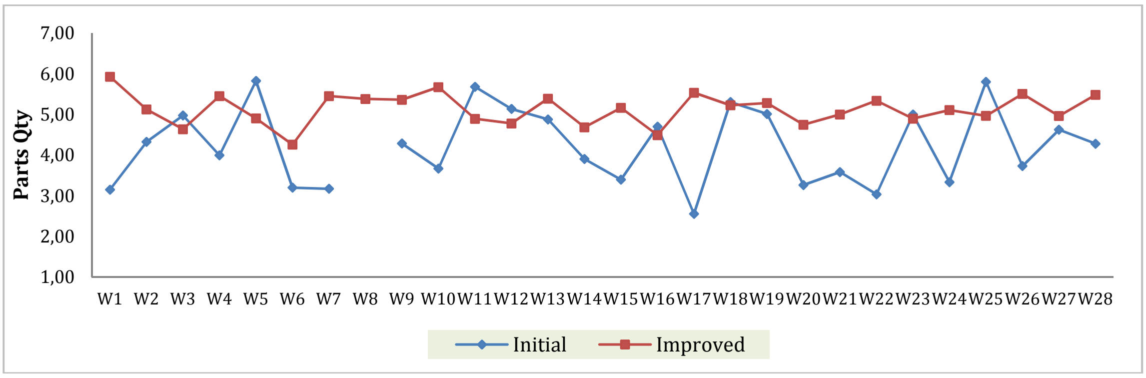

Fig. 10 Production volumes of gears

Table 8 Comparison of production volumes

Part	Desired capacity	Initial capacity	Improved capacity
Corn cutter	98	59	102
Side and face cutter	98	72	111
Module cutter	98	63	112
End mill cutter	98	73	127
Reamers	168	176	165
Drills	168	146	205
Miscellaneous shafts	168	204	183
Gears	152	114	144

8.2 Mean work in process (WIP) inventory

Ideally WIP should be equal to the number of workcentres in a manufacturing setup. An improvement in mean WIP for proposed approach was noted. But it was still greater than no. of workcentres in the system. There were 11 workcentres in the system.

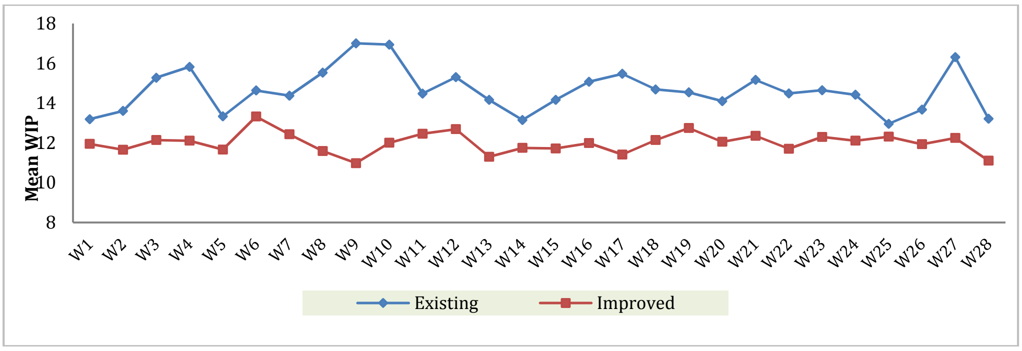

Fig. 11 Mean WIP inventory

8.3 Mean tardiness

This performance measures indicates deviation from promised delivery dates. Mean tardiness is measured in hours and it is for whole period of 28 weeks (Table 9). Comparatively, improved system has shown considerable improvements in reducing the tardy jobs. It is interesting to discuss that despite improvements in arrival times, transportation times, set up times and reduction in WIP, the improved system is also having tardiness.Further investigations showed that there are few tardy weeks for corn cutter, module cutters and gears. There is no tardy week for side and face cutters and drills. But there are many tardy weeks for end mill cutters, reamers and shafts. Although, improved system is having tardy weeks, it is still performing good in delivery of tooling to the major units(Fig. 12).

Table 9 Mean tardiness of tool room

Part	Initial mean tardiness	Improved mean tardiness
Corn cutter	-5755.01	-42.00
Side and face cutter	-4581.63	0.00
Module cutter	-3841.81	-37.29
End mill cutter	-9863.78	-300.86
Reamers	0.00	-360.23
Drills	-2908.78	0.00
Miscellaneous shafts	-39.9704	-201.84
Gears	-5755.01	-42.00

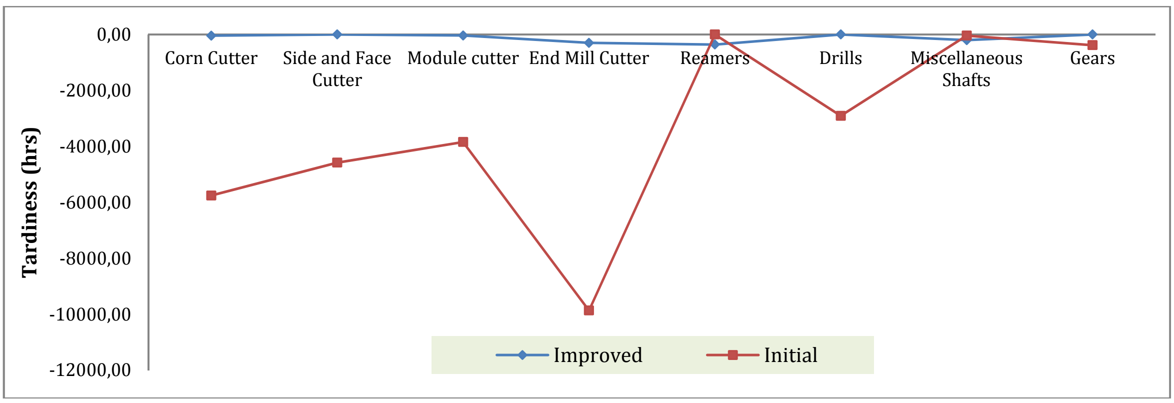

Fig. 12 Mean tardiness for improved and initial systems

8.4 Mean queue times

This performance measure was included to reveal the reasons for tardy jobs, observed in section 8.3. We studied only those work centres that were having long queue times for improved system aswell. Intitally, we studied tool grinding machine (Fig. 13). Except gears and shafts, all parts are visiting this workcentre. Improved system was having mean queue times for the parts , but these were acceptable and can not contribute to tardiness of the job.

Mean queue times on tool mill and vertical grinder indicated the reasons for delayed delivery of parts. End mill cutters and module cutters visited these work centres and were resultantly having tardiness due to longer queue times (Fig. 14).

Tool mills are used for reamers and cutters and longer queue times on this workcentre contributed to overall delay in production of reamers and cutters (Fig. 15).

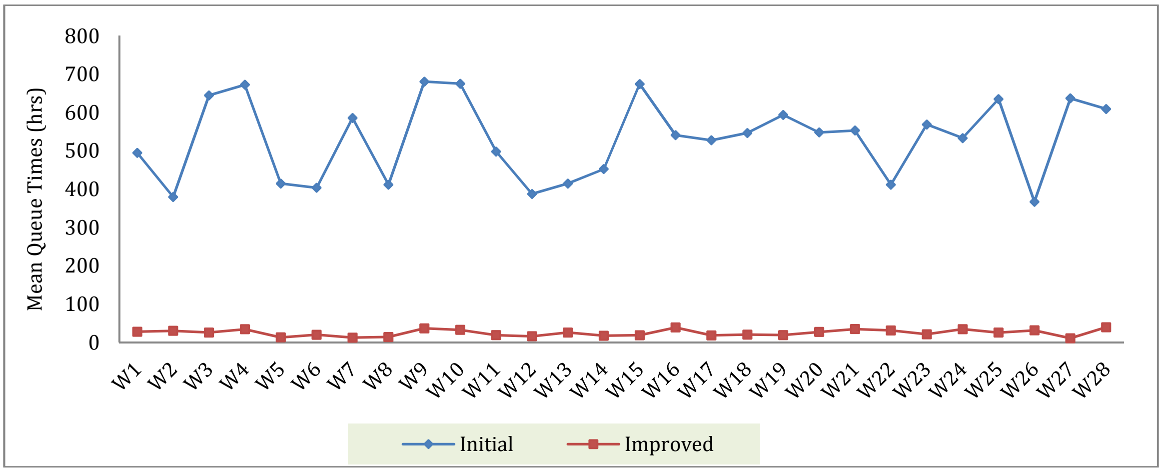

Fig. 13 Mean queue times for tool grinder

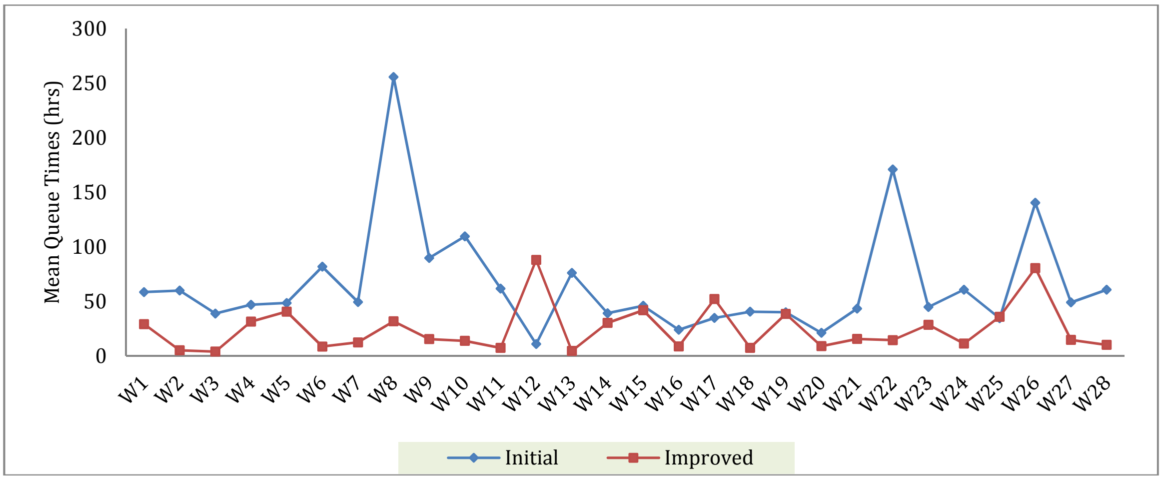

Fig. 14 Mean queue times for vertical grinder

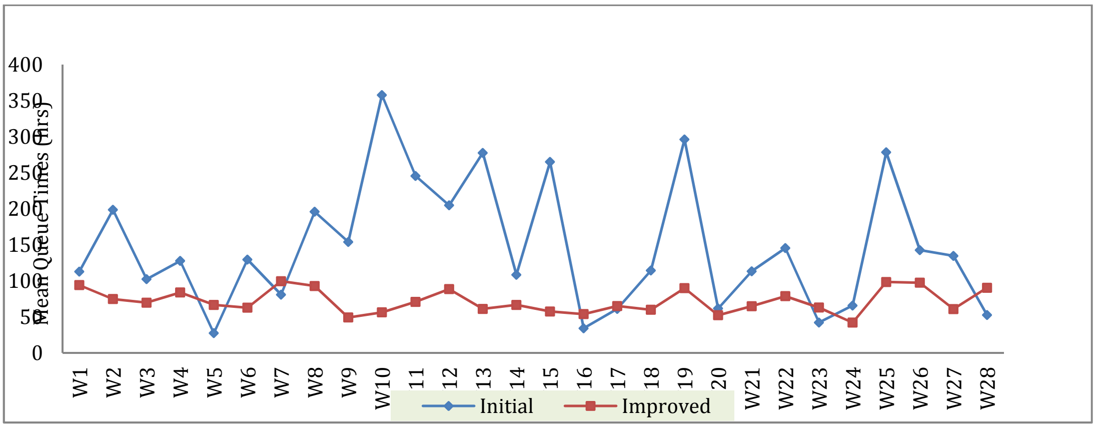

Fig. 15 Mean queue times for tool mill

9. Review and analysis of results

This section is essence of our research and explains lean based system improvement initiatives taken during this study.

Going through results discussed in previous sections, it can be inferred that WIP is larger than workcentres, tool room is having waste of overproduction, toolings are having tardiness and resources are saturated due to long queue times.System improvement strategy for iterative improvement is discussed in Table 11.

This research emphasized on elimination of wastes to improve capacity of organization. Results indicate that proposed system is having waste of overproduction. How to eliminate this waste to improve the system? Overproduction can be eliminated by restricting the issuance of blanks to tool room for value addition. Alternatively, operations supervisor can maintain the counts of parts produced and stop processing on further parts or components. What will be the benefit of controlling overproduction? It will be helpful to reduce queue times on bottleneck work centres and alleviate state of saturation.

Tardiness and larger WIP can be controlled by adjusting arrival times of blanks from heat treatment shops. If workcentres are producing almost desired quantity of products, it is insane to increase arrival times and cause saturation of work centres.Arrival times in imrpoved system are manually managed and can be re-adjusted to suit one piece flow production. Although, control on overproduction will be helpful to improve WIP yet reduction of processing times on saturated workcentres can be equally useful.

Every production unit has 10 % of quality allowance for defective parts and unexpected situations. We have reduced this allowance to 2 percent in our workstudy.

Each workcentre is assigned mean time to failure based on work history of existing system. Preventive maintenance of workcentres can be used to improve this time. An improvement in this time will result in quick processing of toolings on workcentres and will reduce queue times. Mean time to failure can be improved through periodic inspection of workcentres and availability of alternative in case of failures.

This work used this type of system improvement suggestions during each iteration. Last iteration was left to present overall working of proposed approach.

Table 11 Iterative system improvement approach

Serial No.	Lean improvement	System improvement initiatives
1	Elimination of wastes	Overproduction control
2	System improvement	Fixing blank quantity, Adjusting arrival times, Improving process times
3	Defect prevention	2per cent quality waste
4	Total preventive maintenance	Revisiting breakdown times

10. Conclusion and future work

This study has proposed an iterative improvement strategy using lean concepts and methodologies. Although, proposed strategy is for tool room capacity planning yet it can be equally used for other domains as well. Proposed approach was validated through modelling and simulation of tool room. Actual execution of the approach can be used to assess its true suitability. It was assumed that breakdown times of workcentres have been controlled. Inability to control these times in real implementation will deter the performance of our proposed approach. Despite the requirement of defined quantities of toolings for major units, there might occur situations that require additional tooling for normal production process.Our research has also considered this situation. This approach has suggested minor changes in design and layout of tool room to reduce trasnportation of parts and motion of workforce. Besides PDO management, whether senior management of other organizations will be interested to relocate workcentres for suggested changes in layout.This might hamper suitability of our proposed approach in other domains.

System imrpovements in tool room resulted in enhanced production volumes with existing resources. It shows that lean iterative strategy can be used for capacity planning and exploiting the potential of an organization (Table 10 and Fig. 16). An understanding of the results encouraged us to suggest reduction in production of end mill cutters, drills, side and face cutters and module cutters for proposed strategy.

There was an improvement of 28 % in delivery of tooling to major units and 24 % in enhancing the production capability of existing system.Mean WIP was reduced by 18 percent with considerable reduction in queue times. These are remarkable achievements and pave the way for future implementation of this approach in major production workshops too.This research has proven that lean philosophy is also applicable in capacity planning of manufacturing setups. We are currently working on implementation of lean in assembly shop capacity planning of T-80 UD tanks. Since proposed approach believes in continuous improvement until stopping criteria is met, thus same approach was iterated thrice. However, results obtained in second iteration were discussed and lean evaluation process for the third iteration was presented in review section to provide better understanding of the approach. An improvement in the proposed system can also be seen in Fig 17.

Table 10 Performance comparison of systems

Part	Initial capacity, %	Improved capacity, %
Corn cutter	61	104
Side and face cutter	73	113
Module cutter	64	114
End mill cutter	74	130
Reamers	105	98
Drills	87	122
Miscellaneous shafts	121	109
Gears	75	95

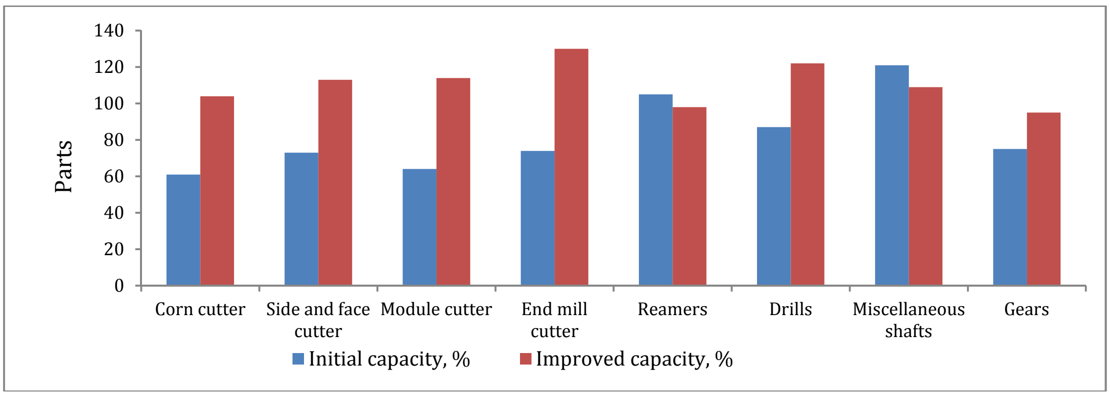

Fig. 16 Improvements in proposed system

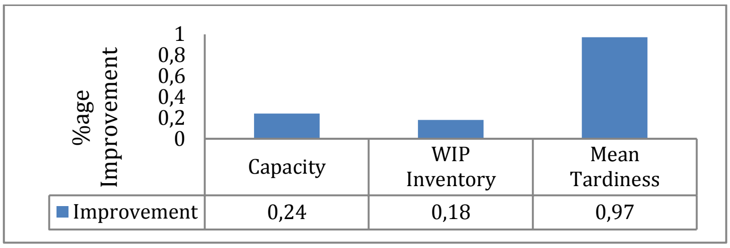

Fig. 17 Improvement in comparison parameter

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Original review paper

The application of service robots for logistics in manufacturing processes

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A B S T R A C T

The introduction of service robots AGVs (automatic guided vehicles) into manufacturing processes is one of the more important qualitative shifts in the automation of transport operations in the manufacturing, assembly lines, as well as storages. Given the large number of applications, service robots in logistics offer a wide range of different technical and exploitative solutions. Service robots AGVs are primarily used for the realization of internal transport processes. Service logistics robots in the manufacturing processes have a very large estimate of the significance of factors when it comes to physical labour reduction. The investment in installing service robots is amortized much faster provided that the service robots work 24 hours a day. The investment in service robots for logistics is repaid within 2-3 years, and such a system works for about 15 years, operating costs are around 2-4 % annual investment, operation availability is approximately 98.5 %, a high productivity, optimized costs and processing time. This paper presents the annual application of service robots in logistics, as well as applications of AGVs service robots with different structures in the manufacturing processes, in confined areas and open spaces, such as shipping containers in ports.

A R T I C L E   I N F O

Keywords:
Service robots
Automatic guided vehicles
Logistics
Transportation
Manufacturing process
Assembly process

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1. Introduction

The automation and modernization of manufacturing processes in industrial plants is carried out in part at improving transport operations in the manufacturing itself. The introduction of service robots represents one of the most significant developments in the automation of transport operations in manufacturing, assembly lines, as well storages.

Also, service robots are used in logistics in hospitals, terminals and freight-transport centres. The AGV service robots (Automatic Guided Vehicles) are prominent. These are service robots-unmanned vehicles that move by means of an automatic control system, usually battery-operated or operate by an electric motor. Sensors on the infrastructure and the vehicle provide information on the location and velocities of the vehicle based on which the control system sends the appropriate commands to the vehicle, so that it could follow the proper trajectories and move with an appropriate velocities.

The weight that AGV can transport ranges from light load of several kg up to 100.000 kg of load. The application of these systems increases the efficiency in the working environment and reduces the costs of labour, energy and system maintenance. Basic advantages of introducing AGV vehicles into the automation of transport operations in the manufacturing itself are the following: reduced labour costs and other operating costs, one AGV vehicle that works in three shifts can save three wages of workers who operate a forklift, increased reliability and productivity – AGV vehicle can work without problems in three shifts without breaks and days off, a reduction of goods damage – AGV has a controlled movement of the vehicle with an accuracy of ± 10 mm, increased safety – since the material handling processes do not require human activity and the vehicle always behaves according to pre-programmed instructions, the minimum the possibility of employee's accidents and injuries, flexibility – unlike fixed (stationary) solutions for material handling, the path by which the AGV moves can be reprogrammed very easily.

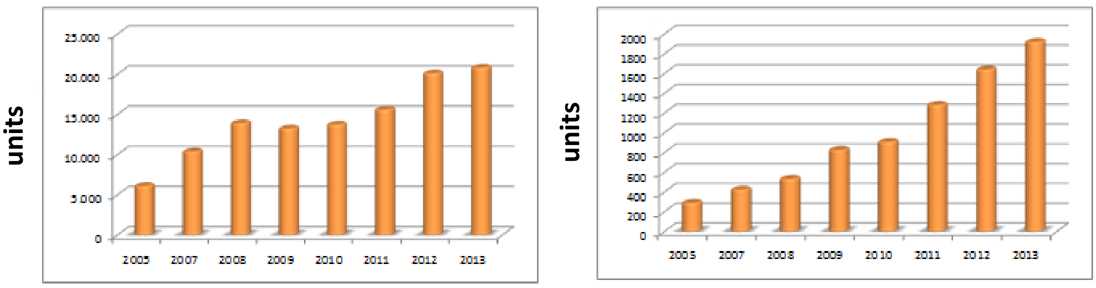
The application of autonomous service robots for logistics involves transport, handling, packaging, sorting and delivery of products. Normally, these robots are installed in industrial plants where they are used to move the working elements, boxes, pallets or tools from machines to machines, shipping areas or storages. Apart from the application in automation of transport operations in the manufacturing itself, these service robots are also used in offices, hospitals, post offices, airports, and other public institutions in which the transport and delivery of various goods is necessary. Equally, they found application in open areas, especially in ports, airports, or transhipment centres [1, 2, 5, 6, 14-16].

2. Review of service robots for logistics in manufacturing processes

In 1995, the International Federation of Robotics (IFR) and the United Nations Economic Commission for Europe (UNECE) adopted a preliminary system for service robots classification according to categories and the ways of interaction with them. The classification of service robots is made in such a way that the service robots are first divided into two groups according to their role in the community, i.e. service robots for personal/domestic use and service robots for professional purposes.

Such a classification was adopted by the ISO. A more detailed classification of these two groups of service robot depends on the type of activity, i.e. areas of application for service robots [1, 4]. Considering that the service robots for logistics in the production processes are classified in the group of service robots for professional, an analysis of application of service robots for professional use will be conducted. This group includes: military service robots, field robots (agriculture, cattle breeding, forestry, etc.), service robots for logistics, service robots for medicine, service robots for professional cleaning, service robots for inspection and maintenance, service robots for rescue and monitoring, underwater systems, mobile platforms for general use, service robots for public relations and other service robots.

Fig. 1 shows the application of service robots in the world from 2005 to 2013. Statistical data shown in the diagrams are obtained from the International Federation of Robotics (IFR), the data of the United Nations Economic Commission for Europe (UNECE), the Organization for Economic Cooperation and Development (OECD), and literature [1, 3-10]. Based on Fig. 1a), it can be concluded that the number of service robots for professional use is increasing every year, so that about 5,000 units was applied in 2005, and 20.000 units in 2013. The service robot application increased four times from 2005 to 2013, i.e. 400 %, which is very optimistic.



a – service robots for professional use   b – service robots for logistic

Fig. 1 Annual supply of service robots for professional use and service robots for logistic

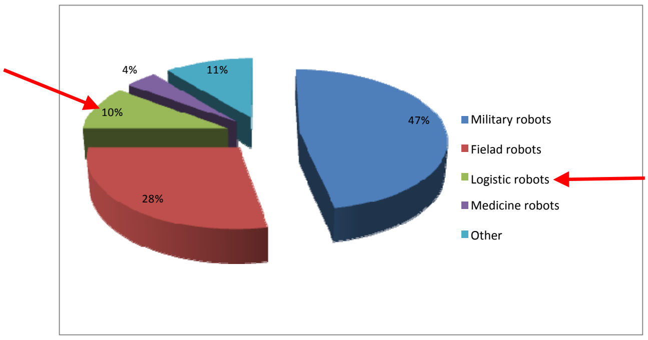


Fig. 2 Perceptual application of service robots for professional use in 2013

It is estimated that the development of information technology, sensor technology, robotic technology, i.e. mechatronics as a scientific domain, will result in a growing trend of service robots for professional use in the future. Service robots for logistics Fig. 1b) have a growing trend from year to year, so that it is predicted that approximately 1,800 units will be installed in 2014 in manufacturing facilities in factories [7-10]. In just nine years, the number of applications for service logistics robots increased nine times. The application of service logistics robots, which are now affordable to smaller companies, aims at reducing labour costs.

Annual analysis of the application of service robots for professional use in 2013, for instance, indicates that 47 % is used for military purposes, 28 % field robots for e.g. agriculture, cattle breeding, etc., 10 % in logistics and 4 % for medicine. The greatest number of robots is currently used for military purposes, agriculture and cattle breeding, which is not a good trend. In future, this trend should go in favour of service robots that are applied in medicine, as well as all other aspects of man's environment in order to help people to get rid of heavy and annoying everyday tasks.

Service robots for logistics in the factories are a very big factor when assessing the significance in reducing the physical labour. The investment to install service robots is amortized much faster provided that service robots work 24 hours a day. Considering the fact that there are 300 beds in one hospital (as it has been estimated) and that 4 million dollars is spent per year to pay workers who push carts (600 work hours is devoted to this task daily), then it can be concluded how much money these institutions would save if they introduced service robot for logistics. The example of investment in service robots for logistics type AGV LTC2-LX is shown in Fig. 3. As it can be seen from the Fig. 3, the investment is repaid in 2-3 years, and such a system works for about 15 years, operating costs are around 2-4 % of year investment, labour availability is approximately 98.5 %, a high productivity, optimized costs and processing time, applicable to all logistics systems, and the maximum load capacity of such a service robot is 450 kilograms. Service robots AGV are equipped with laser, light and sound sensors, which serve to assist in safe transportation, as shown in Fig. 4.

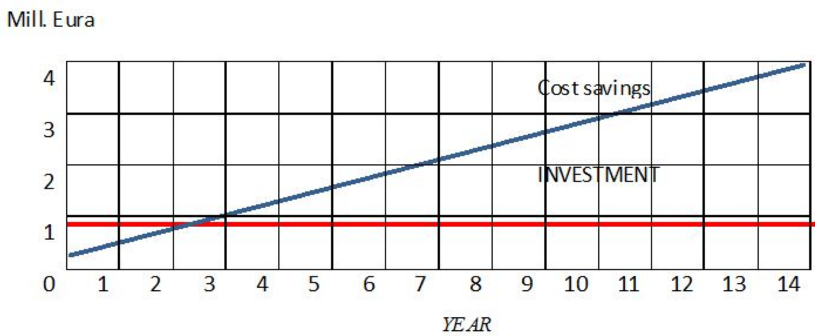


Fig. 3 Investment and amortization of service robots for logistic AGV LTC2-LX

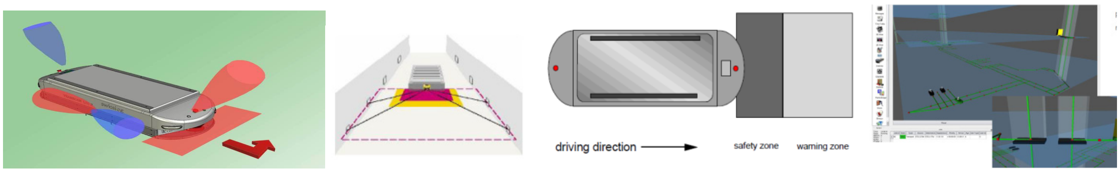


Fig. 4 Service robots for logistics equipped with sensors for communication and guided softer [20]

Due to safety at work, service robots for logistics are equipped with sensors that have a warning zone, which indicates that the obstacle is on the way and reacts with a sound, and a safety zone, where the service robot stops if the obstacle is not removed, as shown in Fig. 4. The safe navigation is a method based on which pathways of automatic guided robots are defined and on the basis of which the robots are controlled to follow a given path.

There are three basic technologies used in commercial systems to guide service robots: imbedded guide wires, with guiding tape, and self-guided robots. In the method with the embedded wire, an electrical conductor (wire) is placed in a small channel that is installed on the surface of industrial flooring. The channel is mostly 3-12 mm wide and 13-16 mm deep. After the wire is set, the channel is filled with cement to align the floor. The guide is connected to a generator that emits low frequency current-voltage signal with a frequency in the zone of 1-15 kHz. The magnetic field is induced along the path which can be monitored with sensors on the leading plate of service robots, as we see in Fig. 5.

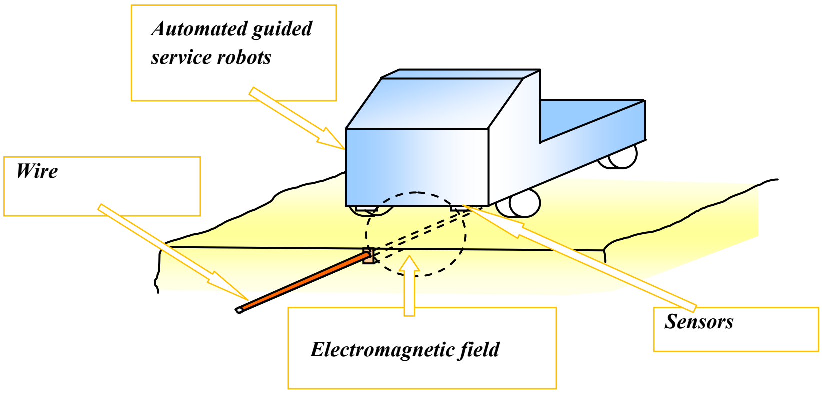


Fig. 5 Sensor with two coils for keeping track of wire magnetic field

Two sensors are installed at the service robot, one on each side of the guiding wire. When the robot is set so that the guide wires are directly between the two sensors, the measured magnetic field is the same for both coils. If the robot moves to one side or another, or if it changes direction of the leading wire, the intensity of the magnetic fields of both sensors will become uneven. This difference of magnetic fields is used to control the motor to guide the robot, which performs certain changes of direction until the signals from the two sensors are re-aligned. When using coloured tapes on the floor to define paths, then service robots use a system of optical sensors capable of tracking colour. The tapes can be glued or painted, or a spray can be used to indicate the path.

The composition of these dyes must be fluorescent components that will reflect ultraviolet light that is sent to the service robot. A sensor installed on the panel of an automatically guided robot detects the reflected light and controls the mechanism for directing the robot to follow the aforementioned tape. These colours have to include fluorescent components which would reflect ultraviolet light sent from the service robot. The tapes are used in conditions where there is electrical disturbance in the plant causing inaccuracy of wire guiding, or when it is not practical to install the wire in the floor. A disadvantage of the taped is that they can be damaged quickly, or dirtied due to the crossing of other vehicles, which causes poor UV light reflection towards the sensor. The good side of the tapes in comparison to the wire is that the tape can be peeled off or repainted, and thus the trajectory of a mobile trolley easily changed.

The introduction of service robots AGV in manufacturing systems is a major qualitative shift in the automation of transport operations in the production, the assembly lines and storages. Given the large number of applications, service robots in logistics offer a wide range of different technical and exploitation solutions. Service robots AGV are primarily used for the realization of internal transport process, so the demand for small space for the movement is of great influence. Objective is to reach the smallest turning radius possible, and therefore special attention is paid to the turning system. With the development of electronics and microprocessor technology, the control unit AGV has evolved as well, which then reduces the need for precisely defined paths through which the service robot AGV moves. For this reason, today's division of service robots AGV based on the navigation system is on systems with a fixed trajectory and systems with free navigation.

Two systems can be used for guiding service robots AGV. The first is navigation using various velocities, most commonly used. In this method, two pairs of wheels are turned, where they may have different velocities. It is similar to the principle of tank rotation, and it is good for operating in a small workspace. The second principle is similar to car guidance. It is more accurate when used in cases of tracking wires, while in that case the automatic guided vehicles cannot make sudden turns. AGV systems with free navigation have a map of the environment in which they operate, which is placed in the memory of microcomputer in a service robot. Path planning is done in a microcomputer based on a preset map of the work environment. Different types of transportation and other tasks that are performed by these systems have given rise to the development of a large number of types of service robots AGV, adjusted to the load or to the working conditions and other characteristics of the applications that are performed. According to the functional characteristics, service robots AVG can be classified into the following groups: tractors, pallet truck, unit load carrier. Service robots AGV tractors are suitable for towing multiple trailers, load bearing capacity is usually 1000-2000 kg, and can be constructed for the capacity up to 20.000 kg. These service robots can be driven by an electro battery, hybrid and combined power with a diesel engine, Fig. 6. In contrast to trucks, service robots AGV dollies for pallets are usually designed to carry a single pallet unit, and can be extended with forks that give the possibility to accept two pallet units, as shown in Fig. 6. Modern solutions have a great autonomy of work, loading and arrangement of pallets, which is a result of the development of microprocessor technology and the support of the management of these systems.

Service robots unit load carrier are autonomous units that are primarily intended for the transport of loads in circumstances where it is necessary to integrate with any other process (acceptance of load from a conveyor belt), or in terms of significantly limited space. These vehicles are not capable to take the load from the floor level, but different solutions are used in such cases, Fig. 6. Special vehicles are based on the same constructive solutions as trucks, except from one difference in adequate adjustment to specific areas of application, as shown in Fig. 7.

Fig. 6 Service robots AGV trucks and pallet trucks [22,23]

Fig. 7 Service robots AGV transportation and special vehicles [27]

Nowadays, big production companies keep finding solutions of AGV system with the possibility of completely autonomous operation in the storage zones, as well loading and arrangement at arbitrary locations, which is accomplished using a set of solutions for the precise positioning and identification both at AGV and in storages. Due to their autonomy, service robots AGV with the possibility of integration in production and assembly lines represent in some way a mobile job posts, which deliver or ship work items properly, according to the technology and work speed in certain areas. Vehicles with possibilities of integration in manufacturing and assembly lines represent in some way a moving work stations, Fig. 8.

Automated vehicles greatly depend on digital data related to jobs and environments in which they operate – mostly small companies which are very difficult to secure. To navigate in the open unlimited space, wireless AGV systems need to know their position at all times and be able to determine the path towards the end point.

Fig. 8 Service robots AGV applied in assembly process [28]

Automated and rail vehicles can be used for transport in industrial plants. Rail system may consist of one or two parallel rail tracks. The existence of rails to navigate such vehicles differs substantially from the automated guided vehicles. A power supply of rail vehicles, as opposed to automatic guided vehicles which have electricity-powered batteries, use the power supply from the electric railway tracks. Apart from automated vehicles, floor and overhead conveyors are used in the transport in a manufacturing process, Fig. 9.

Fig. 9 Rail guided vehicles, floor and overhead conveyers [28]

Conveyors are used when the material must be moved in large quantities from specific locations on a fixed path. This fixed path can be installed on an industrial floor or suspended on a certain structure. Thus, we mostly have floor conveyors and overhead conveyors. There are many different designs of floor ad overhead conveyors. We will mention only some which are used in the process of automation of the production processes: roller conveyors, wheel conveyors, belt conveyors, chain conveyors, and overhead conveyors. Floor roller conveyor moves by means of friction, which is realized between the rollers and the load. In automatic production, the movement is obtained via electric motor.

These motors are usually asynchronous. Since this transport often demands a change of speed of the load, motors are connected to the frequency converters that regulate the speed, and the whole transportation process is most often controlled by the PLC device. Chain conveyors operate on the same principle, with the only difference that the load is placed on the plate and the contact surface is much bigger. Overhead conveyors, Fig. 10, consist of a rail through which the moving chain is driven by a big motor and transmission system, to which different transport carriers are bound or some other forms of material loading. In a continuous transport, we have only a chain that shifts the load from one place to another, i.e. from one treatment to another. Or certain processing demands continuous transit of materials (painting). When one wants to perform more flexible transport, two rails are used, Fig. 10.

Vehicles with telescopic forks, as well as forks with other structures, provide much greater autonomy of handling materials and performing virtually all storages and transport activities such as loading, lifting/lowering, transport and location. Nowadays, big production companies keep finding solutions of AGV system with the possibility of completely autonomous operation in the storage zones, as well as loading and arrangement at arbitrary locations, which is accomplished using a set of solutions for the precise positioning and identification both at AGV and in storages. An automatic storage which is often combined with a distribution system is an automatic version of standard storages.

The transport system delivers material in the system in storage, or takes material from the storage system in sale. A single automatic storage can serve as a repository of both raw materials and finished products. Storage takes place in such a way that a large rectangular robot, so called storage machine, moves through the warehouse. The robot moves between storage racks and lifts cargo on an estimated height designated for a particular product. The systems are fully automated, i.e. all movements and material handling is automated.

Many manufacturers of automated heavy-cargo trucks offer platforms that can be applied in various areas: transport of aircraft parts, containers, building constructions, Fig. 12. Australian Centre for Field Robotics (ACFR) is one of the centres with experience in the production of automated robots for the handling of cargo, including vehicles for carrying containers, cranes and hoists for freight, that are already on sale. An example of this technology transfer is Brisbane AutoStrad terminal, where 14 robotic driverless straddle carriers, called Kalmar E-Drive, are installed.

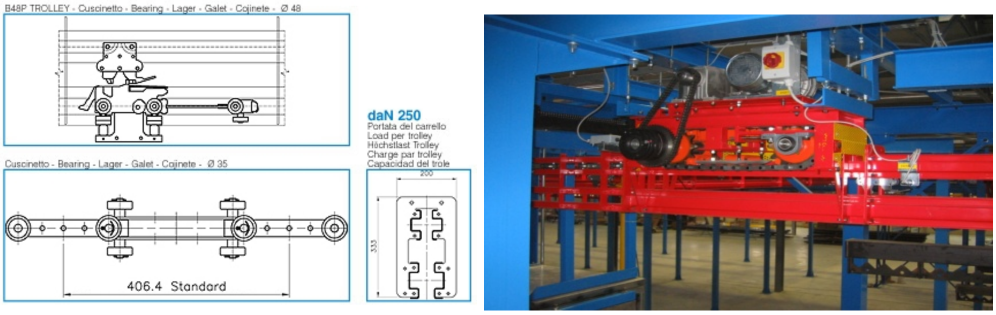


Fig. 10 Implementation of rail and chain (Flowlink company) driving unit of overhead conveyer

Fig. 11 Service robots – AGV with telescopic forks

Fig. 12 Service robots – AGV with telescopic forks

The company "Neobotix" produces service mobile platforms for automation of transport in production processes, and thus a service robot Mobile Manipulator MM-KR16 has been produced [18]. This service robot is configured so that the KUKA industrial robot with six axes is integrated with the mobile platform, as shown in Fig. 13.

The combination of a robotic arm and stable mobile platform enables automation of demanding decentralized tasks, which allows the robot to operate independently up to ten hours.

Service robots in „KIVA Systems" are presented in a bit different approach to business logistics: manufactured goods should not be placed in one specific location, but the pallets, crates and shipments are put on a special bench, and then collected and distributed by many mobile robots. As a result, any product is available to each of the workers at any time. These robotic transport units move with the help of a network of optical markers on the floor, and are in constant contact with the server which enables coordination. When the batteries are low, the transport unit is automatically placed on the charger located in the floor [23].

Automated vehicles greatly depend on the digital data related to tasks and environment in which they operate, which is in most cases very difficult to secure for small companies. Although automated vehicles have not reached the expected level, they can provide their users with safety improvements and business novelty.

Fig. 13 Service robots MM-KR 16 for automoton of manufacturing processes

Fig. 14 Service robots – KIVA systems [23]

Many manufacturers are trying to reduce the individual cost of automated vehicles by offering customers the option of renting these products. This is to reduce investment in business logistics, which in fact does not make any profit for a company. Also, when renting a robot, companies are not required to provide the complex data for robots that perform tasks.

3. Conclusion

By automating and constant modernization of production processes in all industries, the conditions for service robots application are becoming more demanding and complex. Due to the development of new methods and technologies, the use of new materials in all industrial production processes requires new product lines, where service robots are applied in maintenance of certain machines, the transport of materials, assembly and maintenance.

The number of service robots for professional use increases each year, so that about 5.000 units of service robots was applied in 2005, and 20.000 units in 2013. Service robots for logistics demonstrate a growing trend from year to year. Thus, we estimate that approximately 1.800 units of service robots for logistics will be installed in manufacturing facilities in the factories in 2014. Annual analysis of the application of service robots for professional use in 2013, for instance, indicates that 47 % is used for military purposes, 28 % field robots for e.g. agriculture, cattle breeding, etc., 10 % in logistics and 4 % for medicine.

Basic advantages of AGV service robots are: reduced labour costs, increased reliability and productivity, a reduction of goods damage – AGV has a controlled movement of the vehicle with an accuracy of ± 10 mm, increased safety and flexibility – unlike fixed (stationary) solutions for material handling, the path by which the AGV moves can be reprogrammed very easily. The investment in these robotic systems is cost-effective because the investment is repaid in 2-3 years, and such a system works for about 15 years, operating costs are around 2-4 % of year investment, operation availability is approximately 98.5 %, high productivity, optimized costs and processing time, applicable for all logistics systems.

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A grey-fuzzy approach for optimizing machining parameters and the approach angle in turning AISI 1045 steel

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A B S T R A C T

The influence of the machining parameters and approach angle of carbide inserts over tool wear at the flank face, surface roughness and material removal rate are investigated experimentally in this work. The optimum conditions are found out by using a hybrid grey-fuzzy algorithm. The grey relational analysis and fuzzy logic technique are coupled to obtain a grey-fuzzy grade for evaluating multi-characteristics output from the grey relational coefficient of each response. The experiments were designed using Taguchi's design of experiments; a L_9 (3^4) orthogonal array was selected for four parameters varied through three levels. Fuzzy-based reasoning was integrated using the grey approach to reduce the degree of uncertainty. The optimal setting was found out by a response table and the influences of input parameters on the output were determined by Analysis of variance. With the help of this hybrid technique the performance characteristics of the machining process were improved, which is proved by the results from the confirmation experiment.

A R T I C L E I N F O

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1. Introduction

Traditional metal removal process such as 'turning' utilizes a hardened cutting tool to remove unwanted material from the rotating workpiece to obtain the desired shape. During the process the turning parameters viz. cutting speed, depth of cut and feed rate are provided to obtain the desired workpiece at a rapid rate, higher tool life and with producing good quality components [1]. But the chosen machining parameters vary from one workpiece to another, from one machine to another machine and from one operation to another operation such as rough turning and finish turning. Apart from the conditions chosen for machining, the cutting tool geometry also plays a vital role. Alteration in the tool geometry reduces the friction developed between the cutting tool-workpiece and between tool-generated chip, roughness produced at the surface of workpiece, contact area between tool-workpiece, cutting forces generated and heat generated. Along with these conditions, the angle at which the cutting tool approaches the workpiece for machining also influences the output responses obtained such as chip formation and magnitude of cutting forces. The approach angle normally affects the cutting edge length which is in contact with workpiece [2].

Tamizharasan and Senthilkumar [3] analyzed the material removal rate (*MRR*) and roughness in turning AISI 1045 steel using uncoated cemented carbide cutting inserts of different ISO designated cutting tool geometries by performing experiments based on Taguchi's technique.

Ramaiah et al. [4] optimized turning parameters for lower cutting forces and temperature using fuzzy approach during turning Al 6061 workpiece using CNMG cutting tool as per Taguchi experimental design. Hashmi et al. [5] developed a fuzzy logic model for selecting turning parameters in the machining process and applied it to three workpiece materials and four cutting tool materials based on the matrix system. Cabrera [6] investigated the effects of machining parameters using fuzzy model to predict the surface roughness parameters during turning composite material with cutting tools coated with TiN. The influence of temperature at cutting zone over wear at flank area is studied [7] for cutting tools of various geometries while turning AISI 1045 steel.

Raidu et al. [8] developed a fuzzy logic based model for selecting cutting parameters in turning tool and die steel with cemented carbide, ceramic and sintered PcBN cutting tool during hard turning operation. Kalaichelvi et al. [9] presented an on-line cutting tool wear detecting method during turning Al/SiC composite by measuring the spindle motor current based on fuzzy logic approach. Gupta et al. [10] applied Taguchi technique of optimization and fuzzy reasoning in high speed machining of P-20 steel with TiN coated tool for optimizing multiple outputs tool life, power, surface roughness and cutting force considering nose radius of cutting tool and cutting environment. Gokulachandran and Mohandas [11] developed model for predicting tool life based on regression model and fuzzy logic method, when end milling IS2062 steel using P30 uncoated carbide tipped tool using results obtained from experiments conducted based on Taguchi's approach and found that fuzzy model results are much closer to experimental values. Prediction of output responses by using artificial neural network in MATLAB tool is performed with experiments designed using Taguchi's DoE for varying combinations of machining parameters and cutting tool geometry [12].

Simunovic et al. [13] performed face milling experiments on aluminium alloy based on central composite design of response surface methodology and developed regression models for surface roughness and predicted it using artificial neural network model and compared it. Rajmohan et al. [14] designed experiments based on Taguchi's technique and applied grey-fuzzy technique to obtain optimum conditions during drilling aluminium matrix hybrid composites for evaluating multiple responses. Senthilkumar and Tamizharasan [15] carried out finite element simulation study in turning process and optimized the performance of carbide inserts of varying geometries using Taguchi's technique. Ramamurthy et al. [16] optimized wire-EDM parameters during machining titanium alloy by applying grey relational analysis for multiple outputs and found the significant parameters using ANOVA tool. Apart from machining process, this grey-fuzzy method is applied to other complex optimization problems involving more than one response by converting them into a grey-fuzzy reasoning grade.

1.1 Problem identification

It is understood from the literature survey, that machining parameters feed rate, cutting speed, depth of cut, tool geometries such as rake angle, nose radius, relief angle, side cutting edge angle, approach angle of cutting tool [17, 18] have an higher influence on the cutting forces, wear, chatter, surface finish and material separated as chip from the workpiece to obtain the desired shape and size. Hence, for machining a particular material for a suitable application both machining parameters [19] and geometrical parameters have to be optimized [20, 21] to attain better results. From these conditions, the chosen parameters to be analyzed in this work are turning parameters cutting speed, depth of cut and feed rate along with the approach angle with which the cutting tool approaches the workpiece for metal removing during turning AISI 1045 steel [17], a material which is mostly used in industries. The experiments are designed using Taguchi's DoE and by applying grey relational analysis, the multiple output parameters are converted into grey relational grade [22, 23]. Fuzzy logic technique [20, 24] is used to reduce the fuzziness in the output values to obtain a better optimized condition.

2. Material selection

The workpiece material chosen for analysis in this work is AISI 1045, medium carbon steel, with desired properties of strength and hardness and other physical properties. The applications includes component parts for vehicles, shafts, bushings, crankshafts, connecting rods and parts for the machine building and steel for axes, knives, hammers, etc. The Brinell hardness value is 280 BHN. Table 1 shows the AISI 1045 steel chemical composition.

The micrograph of the selected workpiece AISI 1045 is shown in Fig. 1, large grains of pearlite is distributed in ferrite matrix. The micrograph shows that the steel is recrystallized and hot rolled falling into the category of medium carbon steel.

The cutting tool insert chosen for turning AISI 1045 steel is uncoated cemented carbide, CNMG 120408 CT 3000 grade, TAEGUTEC make. Three cutting tool insert holders with various approach angles such as PCLNR (95°), PCBNR (75°) and PCDNR (45°) are used for analysis. The micrograph of carbide insert is shown in Fig. 2, which contains particles of predominant tungsten carbide. During compacting process, voids are present, identified as black areas. Cobalt solid solution is present in between the grain areas. Solid solution phases of TiC and WC are present in the structure.

Table 1 Chemical composition of AISI 1045 steel

Element	C	Si	Mn	Cr	Ni	Mo	S	P	W	V	Fe
% Alloying	0.451	0.253	0.780	0.336	0.040	0.001	0.009	0.011	0.160	0.004	98.406

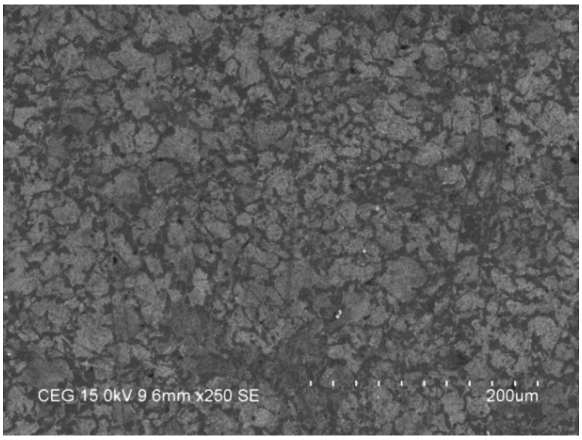

Fig. 1 Micrograph of AISI 1045 steel

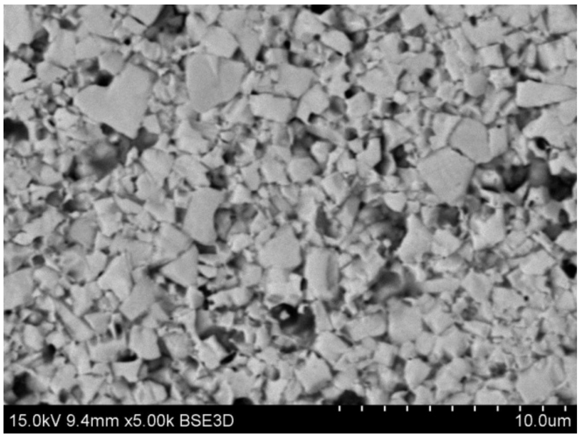

Fig. 2 Micrograph of cemented carbide insert

3. Experimental setup and methodology

Experiments are conducted on a 2-axis CNC Turning center with 350 mm swing diameter, distance between the centres is 600 mm, 4500 rpm spindle speed, 11 kW motor power. After completing the turning operation, with Tool maker's microscope of Mitutoyo make, flank wear is measured. The specification of the microscope is 67 mm working distance, 30× magnification, 13 mm field diameter and 2× objective. Surfcorder SE 3500 is used to measure surface roughness of specifications, measuring distance in X direction is 100 mm, Z is 600 μm, 0.05-2 mm measuring speed and MRR are calculated from the formula given in Eq. 1 in g/min. Fig. 3 shows the CNC turning center and measuring instruments used in this work.

$$MRR = \frac{Weight\ before\ machining - Weight\ after\ machining}{Time\ taken\ for\ machining} \tag{1}$$

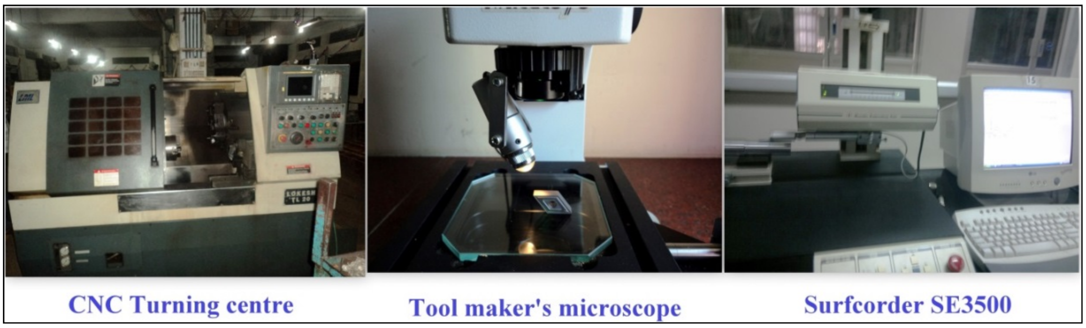

Fig. 3 Turning centre and equipment's used

3.1 Taguchi's design of experiments

Taguchi designed orthogonal arrays (OA's) of various combinations to perform experiments for different parameters and level values. In unique manner, Taguchi developed standard OA's which can be used in various experimental conditions [25-28]. In this work, Taguchi's design of experiments (DoE) is applied for designing the experimental array considering four parameters such as cutting speed, depth of cut, feed rate and approach angle of cutting tool inserts that are varied through three levels. Table 2 shows the chosen control parameters and their selected values [29] for experiments.

Table 3 shows the different combinations of turning parameters and cutting insert approach angle, based on which experiments are conducted as per Taguchi's DoE.

Table 2 Input parameters and their level values

Parameter / Level	Symbol	Level 1	Level 2	Level 3
Cutting speed (m/min)	A	227	256	285
Feed rate (mm/rev)	B	0.432	0.318	0.203
Depth of cut (mm)	C	0.30	0.45	0.60
Approach angle (°)	D	95	75	45

Table 3 Inner array of Taguchi's L_9 orthogonal array

Trial No.	Cutting speed (m/min)	Feed rate (mm/rev)	Depth of cut (mm)	Approach angle (°)
1	227	0.432	0.30	95
2	227	0.318	0.45	75
3	227	0.203	0.60	45
4	256	0.432	0.45	45
5	256	0.318	0.60	95
6	256	0.203	0.30	75
7	285	0.432	0.60	75
8	285	0.318	0.30	45
9	285	0.203	0.45	95

The approach angle of the cutting tool insert, approaching the workpiece during turning is altered by changing the tool holder nomenclature. The nomenclature of the cutting tool holder used for varying the cutting insert approach angle is shown in Fig. 4.

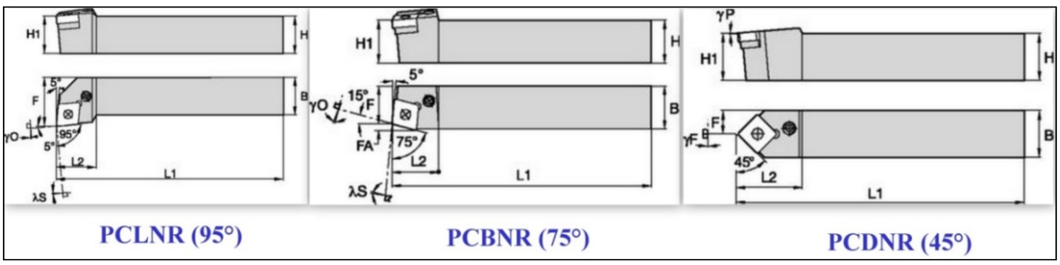

Fig. 4 Cutting tool holders with various approach angles

3.2 Grey relational analysis

For multi-response optimization, Grey relational analysis (GRA) is applied for determining the optimum conditions of various input parameters considered to obtain the best quality characteristics considering single and multiple responses [30-32]. In complex processes having meagre information, for judging or evaluating the performance GRA is applied. Raw data cannot be used in grey analysis, but the data should be pre-processed in a quantitative way for normalizing data for subsequent analysis. For comparison and evaluation, the original sequence is converted between 0.00 and 1.00, in which no information or full information is available. For "Higher-the-better" condition of optimization, the original sequence is normalized as

$$x_i^*(k) = \frac{x_i^0(k) - min\, x_i^0(k)}{max\, x_i^0(k) - min\, x_i^0(k)} \tag{2}$$

where $x_i^0(k)$ is original sequence, $x_i^*(k)$ sequence after data pre-processing, max $x_i^0(k)$ largest value of $x_i^0(k)$, and min $x_i^0(k)$ smallest value of $x_i^0(k)$. For "Smaller-the-better" condition, the original sequence is normalized as

$$x_i^*(k) = \frac{max\, x_i^0(k) - x_i^0(k)}{max\, x_i^0(k) - min\, x_i^0(k)} \tag{3}$$

Grey relational coefficient is calculated after data pre-processing, to express the relationship between actual and ideal normalized experimental values. Deviation sequence is determined by finding the maximum of the normalized values regardless of response variables, trials and replications. Let this maximum value be R, which is known as reference value which is given as

$$R = Max(X_{ijk}) \tag{4}$$

Find the absolute difference between each normalized value and the reference value (R), regardless of the response variables, trials and replications. Let it be Δ_{ijk}, where, i = 1,2,3,…, p and j = 1, 2, 3,…, q and k = 1, 2, 3,…, r.

$$\Delta_{ijk} = X_{ijk} - R \tag{5}$$

Grey relational coefficient is expressed as

$$\zeta_i(k) = \frac{\Delta_{min} + \zeta\Delta_{max}}{\Delta_{oi}(k) + \zeta\Delta_{max}} \tag{6}$$

where $\Delta_{oi}(k)$ is deviation sequence of reference sequence, given by

$$\Delta_{oi}(k) = \| \; x_0^*(k) - x_i^{*0}(k) \; \| \tag{7}$$

$$\Delta_{max} = \max max \; \| \; x_0^*(k) - x_j^{*0}(k) \; \|$$

$$\Delta_{min} = \min min \; \| \; x_0^*(k) - x_j^{*0}(k) \; \| \tag{8}$$

ζ is known as distinguishing or identification coefficient. Generally ζ = 0.5 is used ζ ϵ [0, 1]. Grey relational grade is calculated by taking the average of the determined grey relational coefficient of responses. The grey relational grade is calculated as

$$\gamma_i = \frac{1}{n}\sum_{k=1}^{n} i\, \zeta_i(k) \tag{9}$$

3.3 Fuzzy inference system

Fuzzy inference or fuzzy ruled based system constitutes four models; fuzzification interface, rule base and database, decision making unit and finally a defuzzification interface [33]. Membership functions of the fuzzy sets are defined by the database, which are used in fuzzy rules, inference operation on the framed rules is performed by the decision making unit. Conversion of inputs into degrees of match with linguistic values are carried out by fuzzification interface; defuzzification interface converts the fuzzy results of the inference into crisp output [34]. The fuzzy rule base is driven by if-then control rules with the two inputs and one output i.e.,

- Rule 1: if x_1 is A_1 and x_2 is B_1 then y is C_1 else
- Rule 2: if x_1 is A_2 and x_2 is B_2 then y is C_2 else

  …
- Rule n: if x_1 is A_n and x_2 is B_n then y is C_n

A_i, B_i and C_i are fuzzy subsets which are defined by the corresponding membership functions, i.e., μA_i, μB_i and μC_i. Fig. 5 shows the schematic illustration of the fuzzy inference system, based on which prediction is carried out.

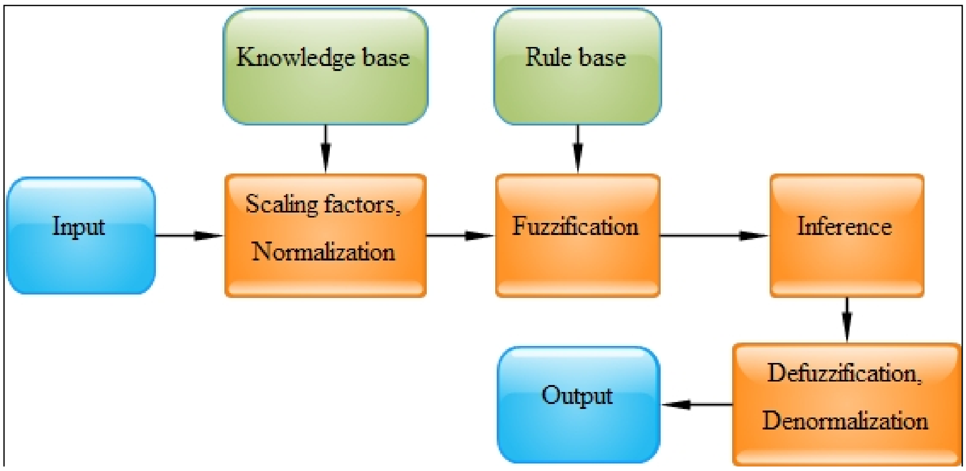

Fig. 5 Fuzzy inference systems

3.4 Analysis of variance

A statistical technique applied to evaluate the difference among the available set of scores is Analysis of variance (ANOVA) [35]. ANOVA is applied to quantity the contribution of chosen input parameters over the output responses [36]. Inferences from ANOVA table can be used to identify the parameters responsible for the performance of the selected process and can control the parameters for better performance. Data analysis is not possible with ANOVA but variance of the data can be evaluated with this statistical tool.

4. Results and discussion

With the formulated L_9 OA designed using Taguchi's DoE, experiments are conducted in CNC turning center. In this study, nine different workpieces are taken and for each level a separate workpiece is used. Using the measuring instruments, the output responses wear at flank face of cutting insert and surface roughness at workpiece surface are measured and using the formulae given in Eq. 1 *MRR* is calculated, which are given in the Table 4.

Table 4 Output quality characteristics measured

Trial No.	Flank wear (mm)	Surface roughness (μm)	Material removal rate (g/min)
1	0.228	1.2	0.368
2	0.301	2.5	0.26
3	0.179	2.1	0.433
4	0.099	1.9	0.341
5	0.098	2.7	0.218
6	0.115	0.6	0.311
7	0.329	3.4	0.207
8	0.222	1.7	0.312
9	0.350	1.6	0.209

The observations made from the output characteristics shows that, when cutting speed is increased from 227 to 256 m/min, flank wear reduces by 55.39 %, surface roughness by 10.35 % and *MRR* by 18.08 %. An increase in flank wear by 188.46 % and surface roughness by 28.85 % is noticed along with a decrease in *MRR* by 16.21 % when cutting speed is further changed from 256 m/min to 285 m/min. A reduction in flank wear by 3.72 %, *MRR* by 17.30 % is observed with an increase in surface roughness by 60.5 % when feed rate is increased from 0.203 mm/rev to 0.318 mm/rev. While feed rate is further increased to 0.432 mm/rev from 0.318 mm/rev, flank wear increases by 5.8 %, *MRR* by 15.97 % with a reduction in surface roughness by 5.78 %.

When depth of cut is changed from 0.3-0.45 mm, flank wear increases by 32.98 %, surface roughness by 71.38 % with a reduction in *MRR* by 18.18 % is obtained. A reduction in flank wear by 19.20 % and increase in surface roughness by 36.65 % and *MRR* by 5.93 % are observed when depth of cut is changed from 0.45-0.6 mm. When approach angle is altered from 45° to 75°, flank wear and surface roughness increases by 48.50 % and 14.05 % respectively with a decrease in *MRR* by 28.45 %. With further increase in approach angle from 75° to 95°, flank wear and surface roughness are reduced by 9.27 % and 15.41 % with an increase in *MRR* by 2.32 %.

In analysing the data, smaller-the-better concept of normalizing is selected while flank wear and surface roughness are considered, since these two responses have to be minimized. But higher-the-better concept is considered for *MRR* since this response should be maximized. Table 5 shows the normalized data of responses after pre-processing and deviation sequence of GRA.

After determining the deviation sequence, grey relational coefficient of each individual response is calculated, which are tabulated in Table 6. For multi-characteristics optimization, which considers all the output responses simultaneously, grey relational grade is derived by considering equal weightages to grey relational coefficient of individual responses. Based on the obtained grey relational grade, ranking is given as shown to identify the best input combination.

From ranking, it is observed that the sixth experiment has the highest grey relational grade of 0.787. Higher grey relational grade obtained indicates that the input parameters chosen for that experiment are considered as the best combination for performing the experiment to obtain better performance characteristics.

Table 5 Normalizing sequence and deviation sequence of GRA

Trial No.	Normalized sequence			Deviation sequence		
	Flank wear	Surface roughness	Material removal rate	Flank wear	Surface roughness	Material removal rate
1	0.484	0.786	0.712	0.516	0.214	0.288
2	0.194	0.321	0.235	0.806	0.679	0.765
3	0.679	0.464	1.000	0.321	0.536	0.000
4	0.996	0.536	0.593	0.004	0.464	0.407
5	1.000	0.250	0.049	0.000	0.750	0.951
6	0.933	1.000	0.460	0.067	0.000	0.540
7	0.083	0.000	0.000	0.917	1.000	1.000
8	0.508	0.607	0.465	0.492	0.393	0.535
9	0.000	0.643	0.009	1.000	0.357	0.991

Table 6 Grey relational coefficient and grey relational grade

Trial No.	Grey relational coefficient			Grey relational grade	Rank
	Flank wear	Surface roughness	Material removal rate		
1	0.492	0.700	0.635	0.609	4
2	0.383	0.424	0.395	0.401	8
3	0.609	0.483	1.000	0.697	2
4	0.992	0.519	0.551	0.687	3
5	1.000	0.400	0.345	0.582	5
6	0.881	1.000	0.481	0.787	1
7	0.353	0.333	0.333	0.340	9
8	0.504	0.560	0.483	0.516	6
9	0.333	0.583	0.335	0.417	7

The fuzzy logic technique of prediction identifies the uncertainties in output responses that are vague, incomplete information and problem imprecision [37, 38]. Reduction of uncertainty present in the grey relational grade can be performed by developing a fuzzy reasoning grade using fuzzy logic approach [39-41]. The fuzzy logic approach is performed to a single grey-fuzzy reasoning grade than considering complicated multiple outputs. Input data and defuzzified output are compared to achieve good prediction accuracy. These fuzzified data's are used by expert systems to answer vague and imprecise questions and describe the ways of assigning functions to fuzzy variables or membership values. Mamdani's inference method is chosen from different techniques available for obtaining membership function values using fuzzy implication operations, known as max-min reference method used for yielding aggregation of fuzzy rules. The defuzzification approach used is centroid method, which is more appealing and prevalent of all available methods [42, 43]. The fuzzy logic technique produces an improved lesser uncertain grey-fuzzy relational grade than the normal grey relational approach, providing a greater value of grey-fuzzy reasoning grade with reduction in fuzziness of data's.

For fuzzifying grey relational coefficient of each response, triangular membership function and fuzzy rules are established. Three fuzzy subsets are assigned for each output response grey relational grade as shown in Fig. 6, by using triangular membership function with three membership functions as Low, Medium and High as shown in Fig. 7.

In fuzzy logic approach, to formulate the statement for predictions, If-Then rule statements are used, which have three grey relational coefficients such as flank wear, surface roughness and *MRR* with one output as grey-fuzzy reasoning grade. The fuzzy subsets that are applied to the multi-response output and the fuzzy subset ranges are presented in Table 7.

Fuzzy logic tool in MATLAB software is used for this grey-fuzzy technique. The grey-fuzzy output is segregated into five membership functions. For activating the fuzzy inference system (FIS) a set of rules are written and to predict the reasoning grade FIS is evaluated for all the 9 experiments. Fig. 8 shows the rule editor in fuzzy environment for predicting the grey-fuzzy reasoning grade, for a given input values of flank wear, surface roughness and *MRR*.

The influence of flank wear, surface roughness and *MRR* based on the if-then rules framed for three membership functions of input functions and five membership functions of output function; grey-fuzzy reasoning grade are given in the surface plot as shown in Fig. 9.

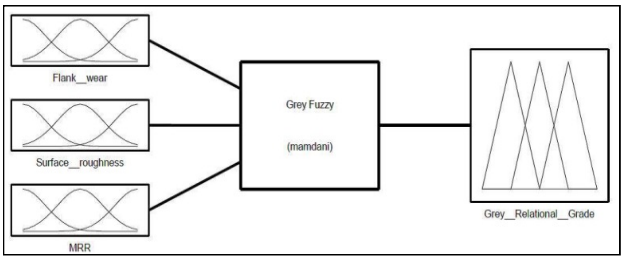

Fig. 6 Fuzzy editor in Fuzzy inference system

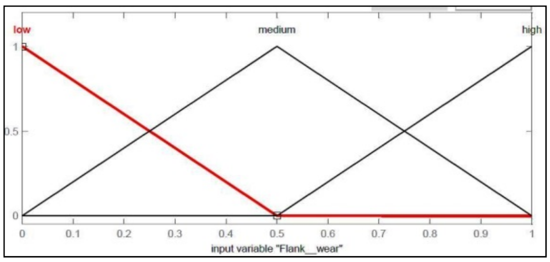

Fig. 7 Triangular membership function applied in FIS

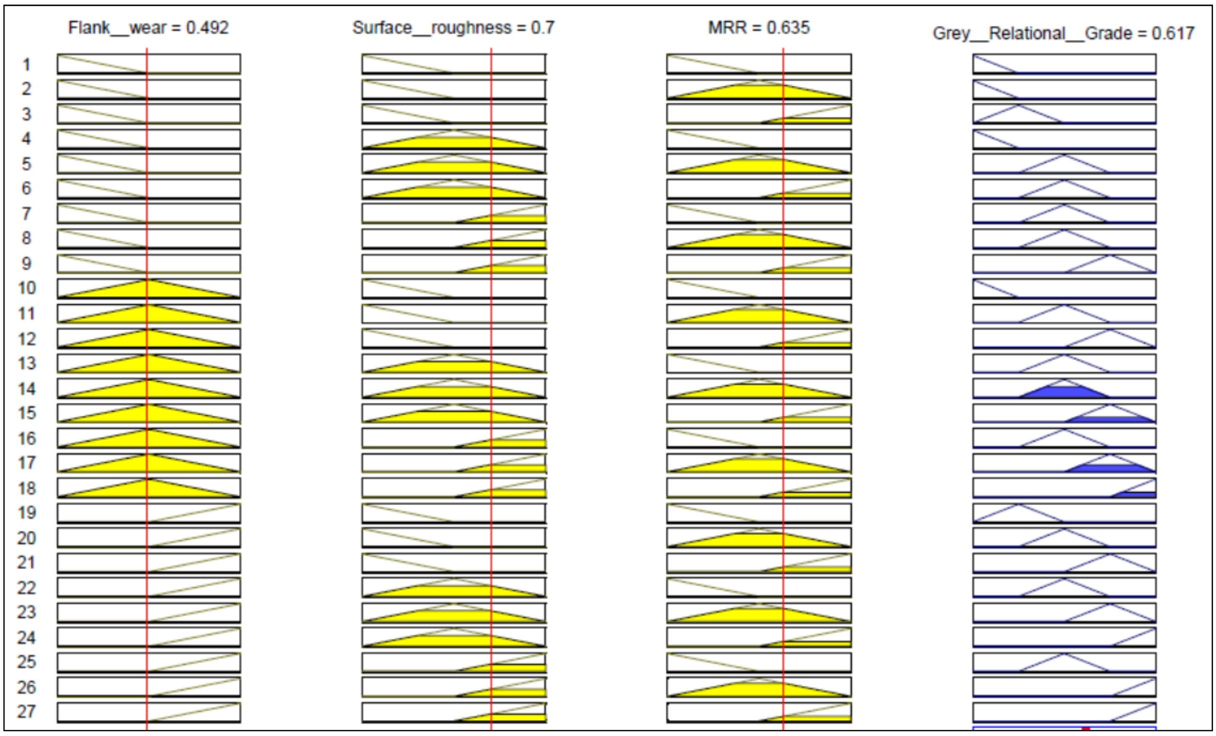

Fig. 8 Rule editors in fuzzy environment

Table 7 Range of fuzzy subsets for grey-fuzzy reasoning grade

Sl. No.	Range of values	Condition	Membership function
1	[-0.25 0 0.25]	Very low (VL)	
2	[0 0.25 0.50]	Low (L)	
3	[0.25 0.5 0.75]	Medium (M)	Triangular function
4	[0.5 0.75 1]	High (H)	
5	[0.75 1 1.25]	Very high (VH)	

Table 8 indicates the determined grey fuzzy reasoning grade from fuzzy logic output and its ranking obtained from the predicted values of FIS. Results of grey relational grade and grey-fuzzy reasoning grade are compared, which shows an improvement in the values of grey-fuzzy reasoning grade, reducing the uncertainty and fuzziness. It is confirmed from the results that the experiment no. 6 has the best combination of machining parameters and approach angle.

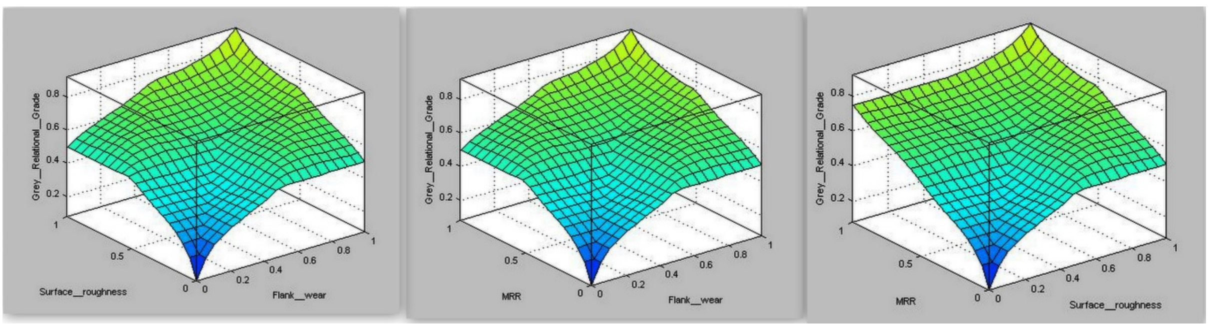

Fig. 9 Influence of output responses on grey-fuzzy reasoning grade

Table 8 Grey-fuzzy reasoning grade

Trial No.	Grey relational grade	Grey-fuzzy reasoning grade	% Improvement	Order
1	0.609	0.617	1.31	4
2	0.401	0.434	8.23	8
3	0.697	0.757	8.61	2
4	0.687	0.746	8.59	3
5	0.582	0.591	1.55	5
6	0.787	0.808	2.67	1
7	0.340	0.404	18.82	9
8	0.516	0.539	4.46	6
9	0.417	0.460	10.31	7

The comparison between the obtained grey relational grade and grey-fuzzy reasoning grade obtained from fuzzy technique is shown in Fig. 10. An improvement in the grey-fuzzy reasoning grade can be observed as compared to the grey relational grade value.

The best level values of various input control parameters are determined from the average values of grey-fuzzy reasoning grade as shown in Table 9, from which the optimal level of each parameter is determined.

From the grey-fuzzy reasoning grade response table, the best level of parameters are identified as cutting speed of 256 m/min, feed rate as 0.203 mm/rev, depth of cut as 0.30 mm and approach angle of 45°, represented as $A_2B_1C_1D_1$. Main effects plot of grey-fuzzy reasoning grade is drawn from the response table, as shown in Fig. 11. It is obvious that the steep slope of cutting speed, feed rate and approach angle shows that they are the most influencing parameters that the other input parameter depth of cut.

The interaction plot or interdependence plot between the input parameters over the calculated grey-fuzzy reasoning grade is shown in Fig. 12. For a cutting speed of 285 m/min, in between cutting speed and feed rate a considerable interaction effect is observed. For all level values of depth of cut and approach angle, a significant interaction exists between cutting speed and depth of cut, and in between cutting speed and approach angle. A higher level of interaction exists between feed rate and depth of cut, and in between feed rate and approach angle for all values. For a depth of cut of 0.30 mm, a noticeable interaction effect is observed between depth of cut and approach angle.

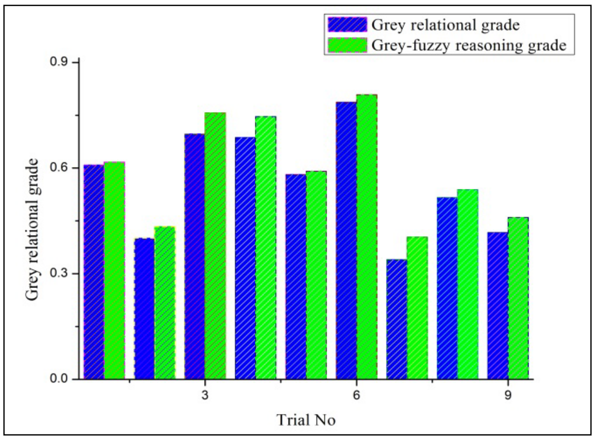

Fig. 10 Comparison between grey relational and grey-fuzzy reasoning grade

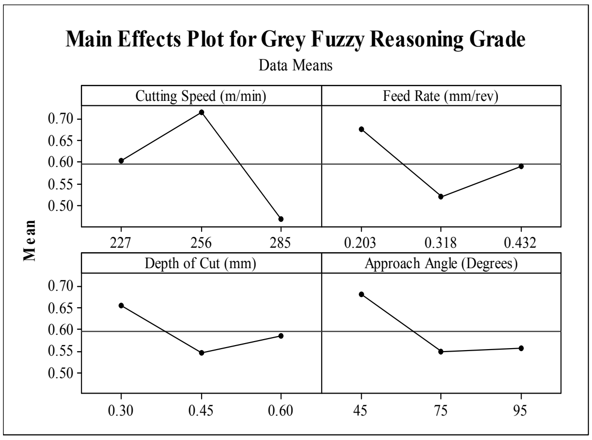

Fig. 11 Main effects plot for grey-fuzzy reasoning grade

Table 9 Grey-fuzzy reasoning grade response table

Level / Parameter	Cutting speed	Feed rate	Depth of cut	Approach angle
Level 1	0.603	0.675	0.655	0.681
Level 2	0.715	0.521	0.547	0.549
Level 3	0.468	0.589	0.584	0.556
Max – Min	0.247	0.154	0.108	0.132
Rank	1	2	4	3

For an approach angle of 45°, a significant interaction is observed between approach angle and depth of cut. In between approach angle and feed rate and in between depth of cut and feed rate, a significant interaction effect is observed for all level values. For an approach angle of 75°, a noticeable interaction effect is observed between approach angle and cutting speed.

To reveal the significance of input parameters the grey-fuzzy reasoning grade obtained is subjected to ANOVA. The ANOVA table shown in Table 10 does not provide enough data's since the degrees of freedom for residual error is zero. This happens when four input parameters with three level values are considered and an L_9 OA is chosen for analysis. Hence ANOVA pooling is to be performed.

Pooling is the process of ignoring an insignificant factor once its contribution is less, which is done by combining the influence of the insignificant factor with the error term. Pooling is a common practice of revising and re-estimating ANOVA results. Pooling is recommended, for two reasons. First, when a number of factors are included in an experiment, the laws of nature make it probable that half of them would be more influential than the rest. Second, in statistical predictions, which encounters two types of mistakes: alpha and beta mistakes. An alpha mistake is calling something important when it is not. A beta mistake is the opposite of an alpha mistake: significant factors are mistakenly ignored. A factor is pooled when it fails the test of significance. Unfortunately, the test of significance can be done only when the error term has nonzero DoF. Pooling is started with the factor that has the least influence. In this analysis, depth of cut is having the least influence; hence it is pooled as shown in Table. 11.

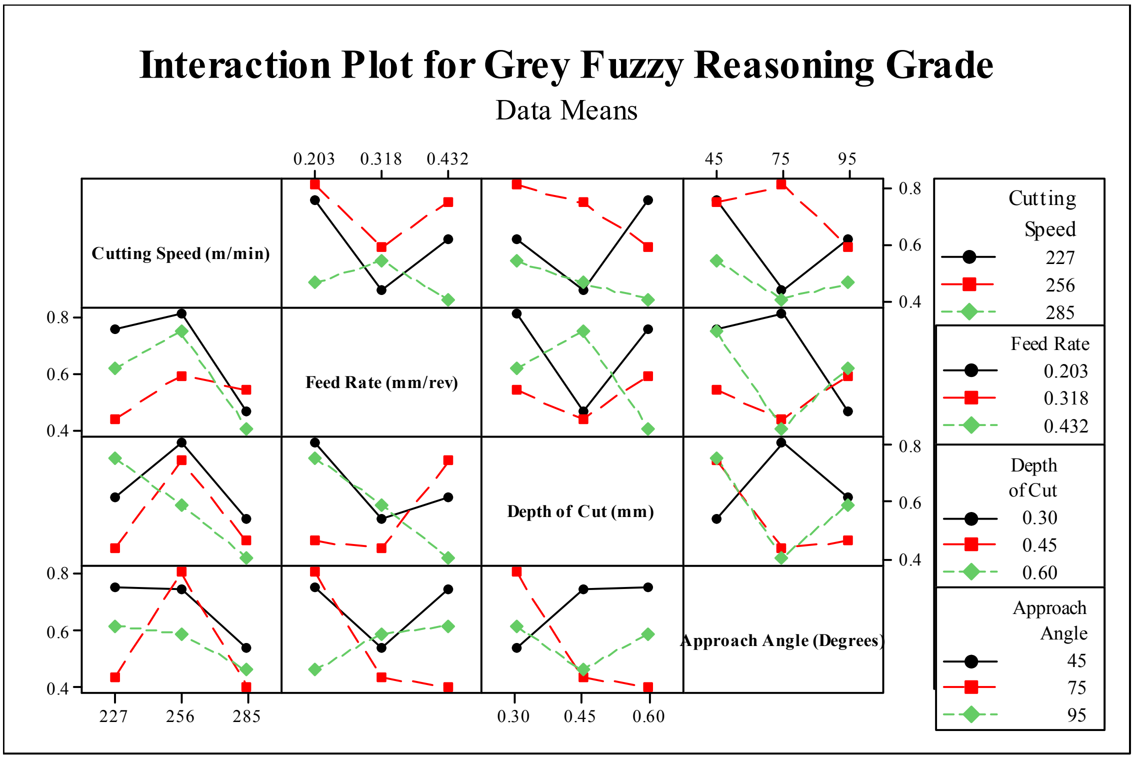

Fig. 12 Interaction plot for grey-fuzzy reasoning grade

Table 10 Analysis of variance for grey-fuzzy reasoning grade (before pooling)

Source	DOF	Seq SS	Adj MS	F	P	% Contribution
Cutting speed	2	0.092018	0.046009	*	*	*
Feed rate	2	0.035588	0.017794	*	*	*
Depth of cut	2	0.018052	0.009026	*	*	*
Approach angle	2	0.033020	0.016510	*	*	*
Residual error	0	*	*			*
Total	8	0.178677				

Table 11 Analysis of variance for grey-fuzzy reasoning grade (after pooling)

Source	DOF	Seq SS	Adj MS	F	P	% Contribution
Cutting apeed	2	0.092018	0.046009	5.10	0.164	51.50
Feed rate	2	0.035588	0.017794	1.97	0.337	19.92
Approach angle	2	0.033020	0.016510	1.83	0.353	18.48
Residual error	2	0.018052	0.009026			10.10
Total	8	0.178677				100.00

From the pooled ANOVA table, it is obvious that the cutting speed is the most influencing parameter that contributes towards the grey-fuzzy reasoning grade by 51.50 %, which is followed by feed rate by 19.92 % and approach angle by 18.48 %. The 'S' value of ANOVA is 0.095 and R^2 value is 89.90 %, which brings a better result.

4.2 Confirmation experiment

After obtaining the best level of machining parameters and approach angle, in order to verify the improvement of output quality characteristics, a confirmation test is performed. The grey-fuzzy reasoning grade estimated is expressed from the output of confirmation experiment. The grey-fuzzy reasoning grade can be estimated using the formulae given in Eq. 10.

$$\mu_{predicted} = V_{2m} + f_{1m} + d_{1m} + A_{1m} - 3\mu_{\text{mean}} \tag{10}$$

where V_{2m}, f_{1m}, d_{1m} and A_{1m} are the individual mean values of the fuzzy-grey reasoning grade with optimum level values of each parameters and μ_{mean} is the overall mean of fuzzy-grey reasoning grade. The predicted mean ($\mu_{\text{predicted}}$) at optimal setting is found to be 0.941.

From the confirmation experiment performed with the same experimental setup, the flank wear decreases from 0.228 to 0.102 mm, surface roughness reduces to 0.92 from 1.2 μm and MRR increases from 0.368 to 0.381 g/min. Thus the experimental grey-fuzzy reasoning grade is 0.772, which shows an improvement by 26.77 %.

Table 12 Initial and optimal level performance

	Initial setting	Optimal level	
		Prediction	Experiment
Setting level	$V_1f_1d_1A_1$	$V_2f_1d_1A_1$	$V_2f_1d_1A_1$
Flank wear (mm)	0.228	-	0.102
Surface roughness (μm)	1.20	-	0.92
Material removal rate (g/min)	0.368	-	0.381
Grey-Fuzzy reasoning grade	0.609	0.941	0.772
% Improvement	-	54.52 %	26.77 %

5. Conclusion

The conclusions derived from the grey-fuzzy logic approach in optimizing machining parameters and approach angle in turning AISI 1045 steel are as follows.

- Experiments are performed based on L_9 (3^4) OA chosen using Taguchi's DoE and analysis is done using grey relational analysis and fuzzy logic approach for optimizing multiple performance characteristics viz. flank wear, surface roughness and *MRR*.
- Grey-fuzzy reasoning grade is acquired to evaluate the multiple responses with the available 27 sets of framed rules, which shows an improvement when compared with the obtained grey relational grade, thereby reducing the fuzziness.
- The optimum level of input control parameters obtained are cutting speed of 256 m/min, feed rate as 0.203 mm/rev, depth of cut as 0.30 mm and approach angle of 45°.
- Interaction plot shows that, a significant level of interaction exists between all the input parameters over each other.
- ANOVA results after pooling shows that the most significant parameter that contributes towards the grey-fuzzy reasoning grade is cutting speed, contributing by 51.50 %, feed

rate by 19.92 % and approach angle by 18.48 %. It is proved that by varying the approach angle of the carbide tool, performance can be improved.

- Improvement in grey-fuzzy reasoning grade from 0.609 to 0.772 confirms the improvement in the turning process with change in turning parameters and approach angle.
- The considerable improvements in the values flank wear; surface roughness and MRR are obtained from the confirmation experiment shows the effectiveness of this grey-fuzzy approach.

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Permanent magnets for water-scale prevention

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A B S T R A C T

Anti-scale magnetic treatment (AMT) is discussed with the emphasis on the construction of magnetic devices and the mechanism of AMT influence on scale formation. Two field cases are reported of mineral-fouling reduction during water heating by using permanent magnets. Instead of hard encrustation on the heated surfaces a powdery deposit was formed because of modified crystal morphology (observed by X-ray powder diffractometry and scanning-electron microscopy). In order to find a proper design for magnets regarding the influencing parameters (a magnetic-field distribution with alternating lines orthogonal to the water-flow and minimal density peaks 0.2 T), cost-effective for actual water-flow capacities, several models with NdFeB magnets were simulated by the finite-element method using the OPERA 15R1 computational program. Two optimized models are presented for moderate capacities: a model with a rectangular gap (a two-row set of rectangular magnets) for capacities from 0.5 m^3/h to 3 m^3/h, and a model with annular gap (annular magnets on a pipe and disk magnets within a cylindrical kernel) for 3.5 m^3/h to 5.5 m^3/h.

A R T I C L E I N F O

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1. Introduction

Mineral fouling is a frequent technological problem during water processing. Encrustation in pipelines reduces the flow capacity, thus requiring more pumping power. When precipitated on heated surfaces it additionally reduces the heat-transfer owing to the insulating effects of the minerals. The predominant scale from ground and terrestrial waters is calcium carbonate owing to its decreasing solubility with CO_2 gas released from the solution when the temperature is increased (e.g. in heat-exchangers) or the pressure is reduced (e.g. during water spraying or in a geothermal well). Its solubility also depends on the *pH*: for instance, when NaOH is added CO_2 forms additional carbonate ions and the precipitation of $CaCO_3$ occurs. Depending on water processing conditions, $CaCO_3$ commonly precipitates in amorphous and various crystalline modifications: rhombus-shaped calcite that may adhere into highly-compact scale; needle-like aragonite that tends to form a brittle scale, but in rigorous thermal and hydrodynamic conditions grows into a hard scale, and spherical vaterite that usually form a powder-like scale.

Economic and environmental concerns have led to the development of alternative physical means for hard-scale prevention: by the usages of permanent magnets [1-5], electromagnetic coils [6-9], electrodes [10, 11], and ultrasonic pretreatment [12]. The common principle of these treatments is the pre-precipitation of calcium carbonate (a homogenous nucleation/coagulation in bulk water) into fine suspended particles that later in critical regions (e.g. under the hot conditions of the heat-exchanger) offer preferable surfaces for crystallisation, depositing as a loosely adhered sludge or being carried further by the water-flow.

Here a modelling of NdFeB magnets for particular water-flow capacities is presented, and certain experiences with field applications are briefly reported. As such treatment does not change the composition of water it is convenient for the food industry, and drinking water installation.

2. Operating principle of the magnetic water treatment

The anti-scale magnetic treatment of hard water has been employed for more than half a century, but the application has sometimes proved to be ineffective due to insufficient data about efficiency requirements [13] and still some influencing factors are unrecognized [14]. The phenomenon is not related to the magnetic-force action on dispersed particles [15]. Summarizing the explanations proposed, the mechanism comprises at least two types of interactions influencing the interfacial processes: magnetically modified hydration of ions and interface surfaces [16, 17], and Lorentz-force action on ions at electrically charged particles [18].

Experimental research under well-controlled laboratory conditions and several field tests under real long-term conditions have been done. A systematic test with artificial solutions passed through a magnetic field (magnetic flux density 0.16 T, exposure time 15 min, at different flow rates of 0.54-0.94 l/min) showed an increase in the total precipitate quantity and in the formation within the bulk solution (instead of incrustation on the walls), but this was strongly dependent on the physicochemical properties of the surface material [1, 2]. There are also other reports that dynamic magnetic treatment (i.e. where water flows through the magnetic field) can be effective at maximums as low as 0.1 T to 0.2 T [3, 19, 20]. The effectiveness of a row of permanent magnets (producing magnetic-field orthogonally to the water-flow) increases, whilst increasing the flow rate (up to 1.8 m/s); and the alternating distribution of the magnetic field seems more effective than in the case of non-inverted permanent magnets [19]. In field applications, magnetic devices are constructed for water-flow velocity, commonly 1 m/s to 2 m/s. The exposition time practically 0.03 s to 1 s at 0.05 T to 0.25 T was taken for hard-scale prevention [21, 22]. In a large-scale test [23], the exposition at 0.15 T was close to 0.1 s. There are some reports about high energy savings, reduced cleaning and process down-time costs, owing to the installations of such devices [24-27].

Furthermore, since magnetic treatment offers a variety of selective influences on different substances and processes, these magnetic devices have much wider possibilities for usage, e.g. during coagulation [28], filtration [29], textile treatment [30, 31], redox [32] and enzymatic processes [33], even fuel combustion [34].

3. Field tests

A self-constructed magnetic device (presented in Fig. 4b) yielded some changes in scale thickness formed the high-temperature heating condition [5, 35], but it proved to be more efficient in various field heat-exchangers in which water was heated maximally to 60 °C. Two cases are reported here. The scales were observed using an AXS-Baker/Siemens/D5005 X-ray Powder Diffractometer, and a FEI – QUANTA 200 3D Environmental Scanning Electron Microscope.

A scale-prevention test: 3 m long hot (close to 80 °C) horizontal pipes in a 5 m high container were cooled by pouring groundwater (0.6 m^3/h, total hardness 25 dH and an outlet temperature close to 40 °C). The encrustation that drastically reduced the heat-transfer predominantly consisted of calcite and goethite FeO(OH) (Fig. 1a). After the surfaces had been mechanically cleaned up, a magnetic device (0.18 m long), was installed onto the cooling-water input: only a smaller amount of powdery aragonite (Fig. 1b) accumulated on the upper surfaces and was washed away periodically by a water-jet.

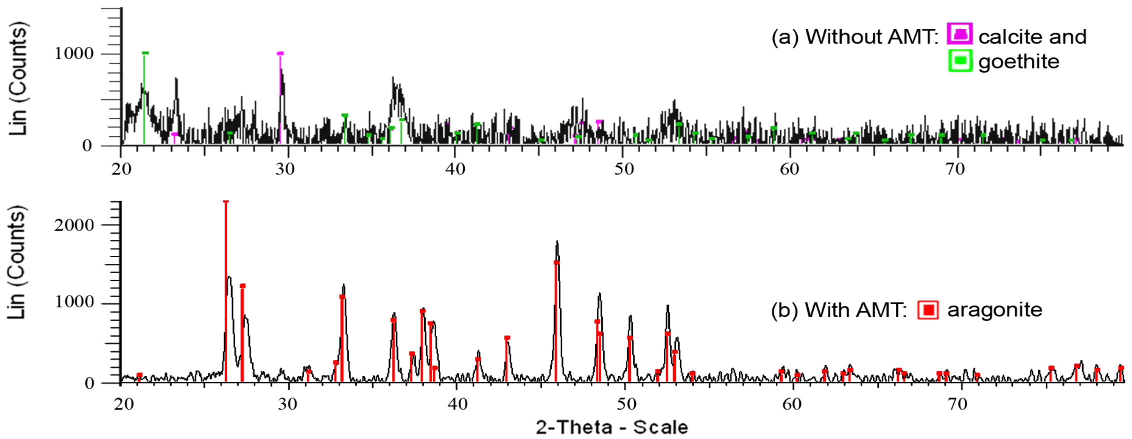


Fig. 1 X-ray diffraction spectrographs of scales from the scale-prevention test

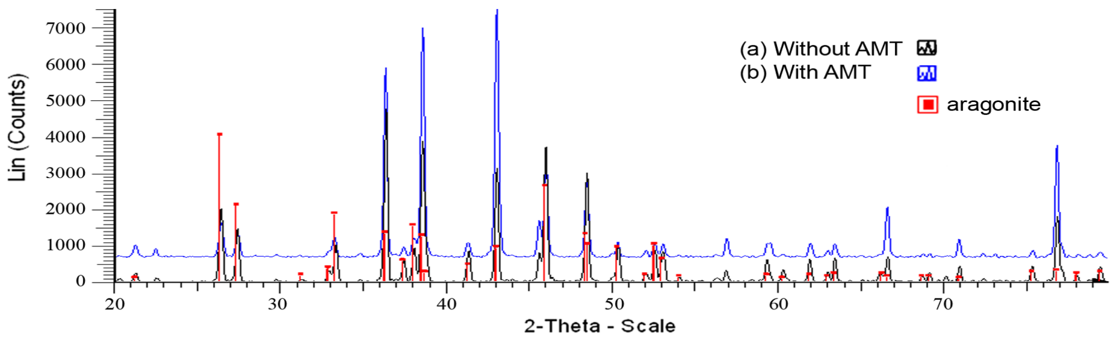
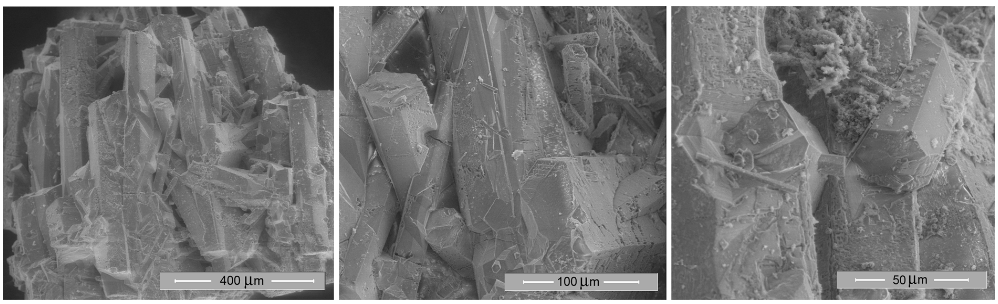
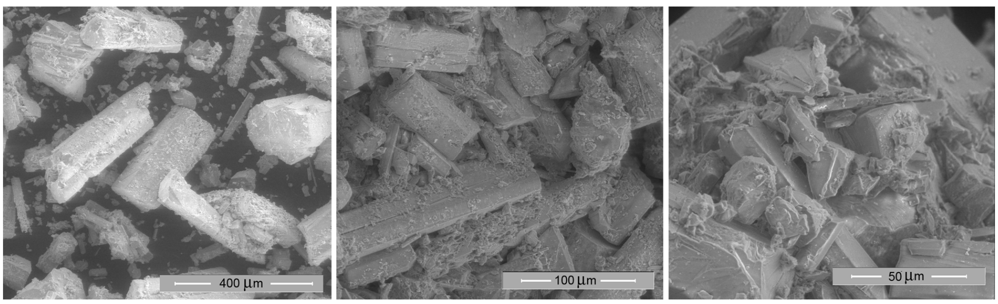


Fig. 2 X-ray diffraction spectrographs of scales from the scale-removal test



(a) Without AMT: A particle broken from porous compact scale



(b) With AMT: A powder of dried slime

Fig. 3 Micrographs of scales from the scale-removal test

A scale-removal test: the region around a sheaf of 12 mm thick spiral pipes of 1.7 m in length and a 3 dm thick cylindrical housing was blocked whilst heating the tap water (1.2 m^3/h, total hardness 17 dH, and an outlet temperature varying from 50 °C to 65 °C) by porous but compact aragonite (Figs. 2a, 3a, needles with predominant diameters of a few-tens μm). By applying the magnetic device (two parallel units, 0.24 m long) without previous mechanical cleaning, the scale was gradually converted into fine slime (Figs. 2b, 3b) and washed away by high-pressure water-flow.

4. Device construction

Different arrangements of permanent magnets were investigated and simulated to find a simple but efficient system for a particular water-flow capacity. After the preliminary dimensioning, the precise dimensions were sought in order to find the proper magnetic-field distribution and the required magnetic flux density, for which the computational program OPERA 15R1 (Vector Fields Software) was used with the finite-element operations [36, 37]. This method enables precise consideration of real 3D-geometry, taking into account the non-linearity of the magnetic properties of the construction materials, and the neighbouring poles' interactions. Since the conditions of the geometrically complex models cannot be determined directly, the geometry must be described by several divided simple geometric elements (i.e. finite elements), as the interference from these neighbouring elements must also be considered. The evaluation of the magnetic flux density along a chosen line or plane yielded local distribution**.** On the basis of these local distributions, a proper configuration for device construction was selected and then optimised by varying the following parameters: the thicknesses of the permanent magnets (i.e., the dimension orthogonal to the water-flow direction); the width (i.e. the dimension parallel to the water-flow direction); the direction of the magnets' magnetisation; the pipe diameter (which influences the distances between the magnets); the distances amongst the magnetic poles, and the thickness of the magnetic yoke. The aim of this procedure was to provide the othogonality of the magnetic lines to the water-flow's direction and alternating orientation from peak to peak, and the following values recommended for efficient AMT: peaks of magnetic-field density, B, as high as possible, at least 0.1 T to 0.2 T; the water-flow velocity in the gap within the range from 1-2 m/s, and minimal exposure time from 0.1 s to 0.2 s.

Permanent NdFeB magnets (with a remaining magnetic flux density of 1.12 T and a coercive magnetic field intensity of 781 kA/m), available on the world market, are strong enough and thermally stable enough to use them for constructing such devices. Low-carbonic steel was selected for the material of the magnetic yoke. The casting was non-magnetic.

The alternating arrangement of rectangular magnets produced magnetic lines transversal to the water-flow. Simulation within the range 0.5-3 m^3/h yielded a rectangular gap as an applicable solution. Results for selected water-flow capacities are summarised in Table 1 and the magnetic-field distribution for a particular case is presented in Fig. 4.

Table 1 Construction solutions for water-flow capacities q_v = 0.5-5.5 m^3/h
(D_{in} is inner diameter of the pipelining; r_{in} is inner radius of the annular gap; r_{out} is outer radius of the annular gap; v_1 is water-flow velocity the pipelining; v_2 is water-flow velocity in the gap of magnetic device).

Standard pipe	Model	Dimensions and water velocity	B peaks
q_v = 0.5-0.7 m^3/h D_{in} = 13 mm, v_1 = 1.1-1.5 m/s	Fig. 4a Longitudinal magnetisation	20 × 20 × 5 mm^3 magnets, 18 × 7 mm^2 gap (1mm wall), v_2 = 1.1-1.6 m/s	0.2 T 0.4 T
	Fig. 4b Transversal magnetisation	20 × 20 × 5 mm^3 magnets, 18 × 7 mm^2 gap (1 mm wall), v_2 = 1.1-1.6m/s	0.43 T 0.6 T
q_v = 1.4-1.8 m^3/h D_{in} = 20 mm, v_1 = 1.2-1.6 m/s	Fig. 4c Transversal magnetisation	25 × 20 × 5 mm^3 magnets, 23 × 12 mm^2 gap (1 mm wall), v_2 = 1.4-1.8 m/s	0.3 T 0.4 T
q_v = 2.3-3.0 m^3/h D_{in} = 25 mm, v_1 = 1.3-1.7 m/s	Fig. 4d Transversal magnetisation	30 × 20 × 5 mm^3 magnets, 28 × 15 mm^2 gap (1 mm wall), v_2 = 1.5-2.0 m/s	0.25 T 0.33 T
q_v = 3.5-4.5 m^3/h D_{in} = 30 mm, v_1 = 1.4-1.8 m/s	Fig. 5 Annular gap	r_{out} = 25 mm (1.75 mm wall), r_{in} = 18 mm (1 mm wall), v_2 = 1.0-1.3m/s	0.2 T 0.4 T
q_v = 4.5-5.5 m^3/h D_{in} = 32 mm, v_1 = 1.5-1.9 m/s		r_{out} = 24 mm (2.75 mm wall), r_{in} = 18 mm (1 mm wall), v_2 = 1.5-1.9m/s	

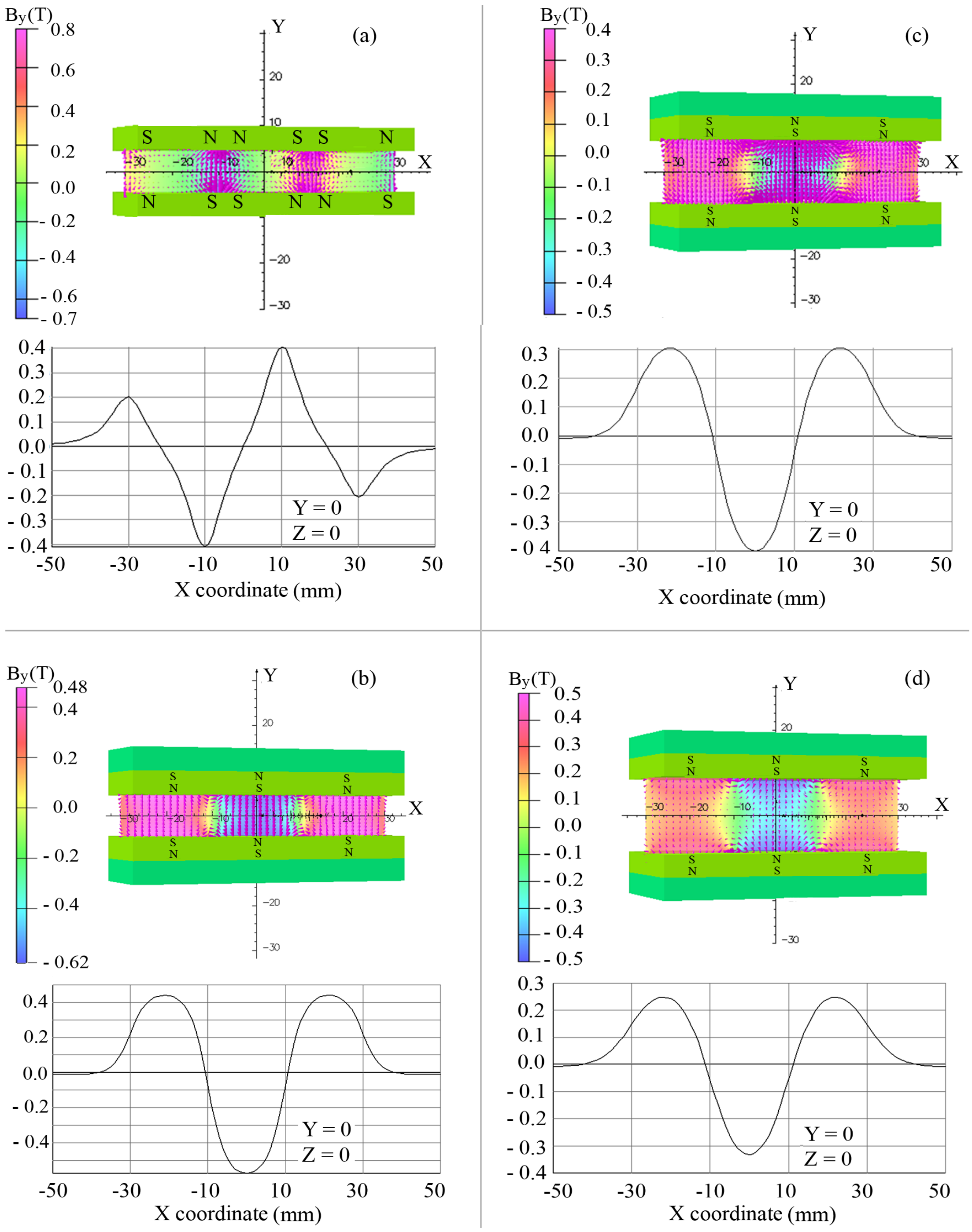


Fig. 4 Distribution of the magnetic-field within the rectangular gap (60 mm long) between two rows of rectangular magnets (three pairs) and the Y-component of magnetic- flux density along the axis of the gap, B_y.

The taken gap, a little wider than the inner-pipe's diameter, provides velocity below the upper threshold, whilst the gap's height optimises the magnetic-field's strength and the hydrodynamic pressure loss.

The model with transversally-magnetized magnets (Fig. 4b) provides a stronger magnetic-field than in the case with the longitudinally-magnetised, at practically the same dimensions (Fig. 4a). In the cases with longitudinal magnetisation, the magnetic-field within the gap is strengthened by a ferromagnetic plate, which concentrates the magnetic flux. In contrast, the magnetic-field in the model with longitudinal magnetisation may be weakened by an eventually present ferromagnetic material in the vicinity of the magnetic device.

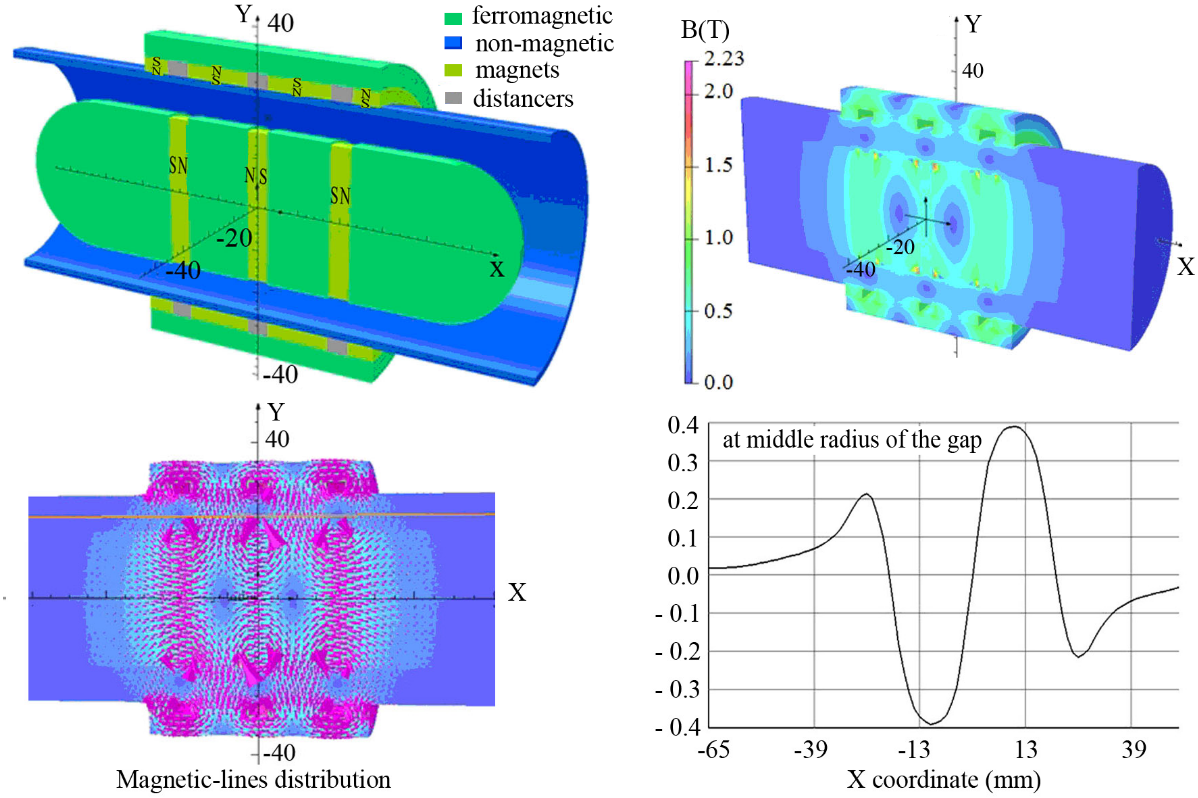


Fig. 5 Distribution of the magnetic field within the annular gap between a ferromagnetic kernel (with inserted disc magnets – three transversely-magnetised, with radii 17 mm and thickness 5 mm) and a 75 mm long ring (with inserted annular magnets – two rings with thickness 15 mm, two rings with thicknesses 7.5 mm and outer radii 30 mm).

The number of successive magnetic pairs is determined by the exposure-time requirement, e.g. 6 to 15 of pairs are needed in the case of 4b.

Water with flow capacities that are not presented in Table 1 can be treated by a parallel pair of smaller units (where the magnetic-field is stronger on account of higher hydrodynamic pressure loss) or by one bigger but weaker unit. In an extreme event, for instance, case 4d can also be applied for Pipe 2, where the water velocity in the gap is lower than the v_2 given in the table, thus requiring a smaller number of magnetic pairs, i.e. from 5 to 12.

The simulation within the range 3.5-5.5 m^3/h yielded an annular gap as a hydro-dynamically more favourable solution. The system of annular and disc magnets is presented in Fig. 5.

5. Conclusion

Since magnetic treatment has a variety of selective influences on different substances and processes, its application has wide potentials.

Constructing a magnetic device for scale control at specific water-flow, some operational requirements, such as a sufficiently strong magnetic-field with proper flux distribution and a long exposure time, must be considered. This paper provided a review of models based on real operational data and material characteristics. For low capacities a model with parallel rows of transversely-magnetised magnets was proven to be a very simple solution; whilst for more than a few m^3/h the model with narrow annular gap is more convenient for providing the required magnetic field at an acceptable pressure loss. The construction and installation is relatively easy, whilst the life-time is long and without any energy consumption.

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Using entropy weight, OEC and fuzzy logic for optimizing the parameters during EDM of Al-24 % SiC_P MMC

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A B S T R A C T

In this paper the multiple methodologies are used viz. Entropy weight measurement, Overall evaluation criteria (OEC), and fuzzy logic for optimizing the process parameters during Electrical discharge machining (EDM) process of Al-24 % SiC_P metal matrix composite (MMC). Three process parameters like as peak current, pulse on time and flushing pressure are considered as input variables whereas material removal rate, tool wear rate, radial over cut and surface roughness are response variables. Central composite design (CCD) is used as the design of experiment (DoE) for conducting the experiments using different combinations of input variables of three levels for predicting responses. The individual weightage of each response is calculated using the Entropy weight method and normalization of responses were carried out with the same weightage of responses using OEC. Finally fuzzy logic was used to obtain a single numerical index known as the Multi performance characteristics index (MPCI). The Analysis of Variance (ANOVA) was used to find the significances of process parameters on the responses. The second-order mathematical model was developed using response surface methodology for predicting the results. Moreover, a confirmation test was carried out to check the effectiveness of the presented approach.

A R T I C L E I N F O

Keywords:
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1. Introduction

Aluminium alloy is a monolithic material used in different industrial applications because of its light weight and high resistance to chemical degradation. The reinforcement of silicon carbide (SiC) particulate in aluminium matrix improves the strength and other properties of Metal matrix composite (MMC). The Al-SiC_P composite is one of the advance composite materials that possess superior physical and mechanical property in compare to other conventional material. Al–SiC_P MMC is used in various fields like automobile, aerospace, defence, sports, electrical appliance and other industries [1, 2]. As the strength and other properties of MMC increases, the conventional machining process is puts into a limit. Therefore, electrical discharge machining (EDM) process is one of the alternatives for machining the same. EDM is a non-conventional machining process based on the principle of thermoelectrically energy. In EDM process any complicated complex shapes with high accuracy irrespective the hardness of the work piece can be machined. During this process a series of spark continues in between work piece and tool electrode in a dielectric medium. As a result material is removed from the work piece due melting and vaporization of the materials in the shape of tool on the work piece [3-5].

It is necessary to select the appropriate process parameters to get the desired dimensional accuracy with a reduction of tool wear and improved surface quality. Among the several researchers, Mir et al. [6] studied the effects of pulse on time, discharge current and concentration of aluminium powder addition into dielectric medium on surface roughness (SR) during machining of H11 steel. They optimized the process parameters by using RSM and concluded that the *SR* increases with increase in concentration of aluminium powder. Karthikeyan et al. [7] developed a mathematical model for the response characteristics like *MRR*, *TWR* and SR using the process parameter such as current, pulse duration and the percent volume fraction of SiC. Singh [8] used L18 orthogonal array and Grey relational analysis to investigate the effects of pulse current, pulse on time, duty cycle, gap voltage and tool electrode lift time on the responses like *MRR, TWR* and *SR* during the EDM process of 6061Al/Al2O3p/20P composites. It has been found pulse current is the most effective parameter among the other. Shukla et al. [9] studied the micro structure of Titan 31 at different process parameters like elevated temperature, cross head speed and angle to rolling for analyse the influences of formability at different tensile test. The results of the formability test are optimized by using Taguchi and OEC method. Aliakbari et al. [10] used Taguchi L_9 method to study the effect of three variables like peak current, pulse on time and electrode rotational speed on responses such as material removal rate, electrode wear rate, surface roughness and overcut during rotary EDM. They proposed a new methodology to optimize the multi-objective problems, i.e. OEC method. Kiran [11] analysed an ergonomic evaluation of Kitchen tool by using Taguchi L_9 technique and the desirable condition are evaluated by using OEC method. Shahbazian et al. [12] applied Taguchi L_{18} experimental design approach to analyse the five operating variables of Batch emulsion Polymerization of Vinyl chloride and optimize the responses by OEC method. Yen Yee et al. [13] deals with the multi response problems during the fabrication of super capacitor. They followed the Taguchi-Genetic Algorithm approach to analyse the weight signal-to-noise ratio and the results are optimized by OEC method. Haddad et al. [14] studied the irradiation conditions of Ultra-high-molecular-weight polyethylene composite by using four process variables followed by L_9 orthogonal array and the responses are optimized by OEC method. Jangra et al. [15] used Taguchi L_{18}, grey relational analysis and entropy weight method to optimize the multiple performance process parameters such as taper angle, peak current, pulse-on time, pulse-off time, wire tension and dielectric flow rate on *MRR*, SR, angular error and *ROC* during WEDM of WC-5.3 % CO composite. Sivasankar et al. [16] optimized the machining characteristics by using entropy based grey relation analysis during EDM of hot pressed ZrB2. Majhi et al. [17] investigated the effect of machining parameters like pulse on time, pulse off time, discharge current on *MRR*, *TWR* and *SR* of AISI D2 tool steel using Grey relational analysis and Entropy measurement method during EDM process. Puhan et al. [18] investigated the influences of four process parameters like discharge Current, pulse duration, duty cycle, and flushing pressure on *MRR*, *TWR*, SR and circularity during EDM process of Al-SiC MMC. They optimize the parameters by principal component analysis (PCA) with fuzzy inference system and ANOVA is applied to study the performance characteristics of the machining characteristics. Majumder [19] used Taguchi L_9 method to find the effect of input parameters such as pulse current, pulse on time and pulse off time on the output *MRR* and EWR by using fuzzy logic and particle swarm optimization (PSO) method during EDM of the AISI 316LN stainless steel. Khalid et al. [20] studied the effect of current, pulse on time and pulse off time on the three output variables *MRR*, *TWR* and R_a during EDM of three materials such as stainless steel, C40 Carbon steel and SKD61. They optimize the process parameters by fuzzy logic evolutionary strategies and state the proposed methodology is a benchmark to solve the multi-objective problems. Laxman et al. [21] proposed the fuzzy logic method to correlate the influences of the process parameter like peak current, pulse on time, pulse off time and tool lift time on *MRR* and *TWR* during machining of titanium super alloy by EDM. Sengottuvel et al. [22] investigate the effect of pulse on time, pulse off time, peak current, flushing pressure and electrode tool geometry on *MRR*, *TWR* and SR during EDM. They optimized the parameters by using desirability approach with fuzzy logic. Dragan et al. [23] studied SR to know the effective process parameter like discharge current and pulse duration of manganese alloyed cold-work tool steel by fuzzy logic and Neural Network in EDM. Rao et al. [24] applied fuzzy logic methodology to compare the *MRR*, *TWR*, R_a, HRB experimental result with the predicting result of AISI 64430 (HE 30) aluminium during EDM. Pradeep et al. [25] used the L_{27} orthogonal array and fuzzy logic method for optimization of the process parameter like pulse current, pulse on time and pulse off time with the multi responses variables *MRR* and R_a during EDM.

Based on the literature review the objective of the present work is carried with an experimental investigation on electric discharge machining of Al-24 % SiC MMC by using entropy weight measurement, OEC and fuzzy logic technique. The aim of this paper is to convert the multi-characteristics problem to an equivalent single response to empirically analyse the effects of peak current, pulse on time and flushing pressure on the metal removal rate, the tool wear rate, radial overcut and surface roughness. Also the second order mathematical model is developed based on response surface methodology to check the significance of the models.

2. Experimental details

2.1 Material preparation

The materials are prepared by using commercial pure aluminium with purity 99 % and silicon carbide having the average particle grain size is 0.0228 mm. The composite materials are fabricated by using stir casting method on the basis of 24 % weight fraction of SiC_p and remaining weight as aluminium alloy. In this process the molten aluminium and SiC_p are stirred at 400 rpm for uniform distribution of the SiC_p in aluminium matrix. After completion of stirring process the molten composite material is poured in to the mould cavity to get desired shape of specimen.

2.2 Process parameters and design

Based on the literature survey the experiments are conducted with three process parameters having three levels of each parameter. Central Composite Design (CCD) has been used as the design of experiment (DoE) for conducting the experiments. As per the CCD, total number of experimental runs is 20. The process variables with their actual values on different levels are shown in the Table 1.

Table 1 Process parameter and their levels

Parameters	Symbols	Units	Levels				
			-1.682	-1	0	1	1.682
Peak current	I_p	A	3.2	10	20	30	36.8
Pulse on time	T_{on}	µs	116	150	200	250	284
Flushing pressure	F_p	kg/cm²	0.164	0.3	0.5	0.7	0.836

2.3 Experimental method and results

The experiments are conducted in an electrical discharge machine (Model MIC-432CS CNC manufactured by ECOWIN, Taiwan) at CIPET, Bhubaneswar. The samples are prepared with 40 mm diameter and 10 mm thickness. For machining the work-piece, electrolyte copper is used as the tool electrode having average diameter 25.4 mm. Each work piece is machined up to the depth of 2 mm and the machining time is recorded in the timer of EDM. The weight of the work piece and tool are measured before and after the experiment by using digital (METLERPM 200) weighing machine. The diameter of each tool is measured before machining and the hole diameter is measured by a profile projector after machining of work-piece. The surface roughness R_a is measured by MITUTOYO surface roughness tester.

The following mathematical relation are used for evaluation of responses such as material removal rate *MRR* in mg/min, tool wear rate *TWR* in mg/min, and radial over cut *ROC* in mm as shown in below.

$$MRR = \frac{W_b - W_a}{t} \tag{1}$$

where W_b and W_a are weight of work-piece before and after machining in mg, respectively, and t is machining time in min.

$$TWR = \frac{T_\mathrm{b} - T_\mathrm{a}}{t} \tag{2}$$

where T_b and T_a are weight of tool before and after machining in mg, respectively, and t is machining time in min.

$$ROC = \frac{D_\mathrm{t} - D_\mathrm{h}}{2} \tag{3}$$

D_t is tool diameter before machining (mm), and D_h is hole diameter after machining in mm.

The experiments results with their value are shown in Table 2. The experimental results are shown in Table 2 as per the Eq.1 to Eq.3.

Table 2 Experimental design and results

Expt. No.	T_{on} (µs)	I_p (A)	F_p (kg/cm²)	*MRR* (mg/min)	*TWR* (mg/min)	*ROC* (mm)	R_a (µm)
1	150	10.0	0.300	195.579	6.942	0.065	10.994
2	250	10.0	0.300	356.731	0.905	0.098	11.811
3	150	30.0	0.300	1279.661	18.525	0.073	17.962
4	250	30.0	0.300	1194.400	8.400	0.081	18.461
5	150	10.0	0.700	119.020	0.304	0.037	9.798
6	250	10.0	0.700	1028.201	0.662	0.050	16.126
7	150	30.0	0.700	1680.000	18.583	0.075	17.702
8	250	30.0	0.700	1393.617	18.638	0.088	22.482
9	116	20.0	0.500	736.872	13.687	0.058	11.21
10	284	20.0	0.500	1057.837	3.347	0.086	20.095
11	200	3.2	0.500	151.250	0.310	0.048	6.124
12	200	36.8	0.500	1955.721	25.836	0.090	21.738
13	200	20.0	0.164	717.916	7.424	0.089	14.298
14	200	20.0	0.836	1183.833	10.946	0.048	19.366
15	200	20.0	0.500	769.242	7.692	0.071	16.105
16	200	20.0	0.500	755.242	7.792	0.069	16.135
17	200	20.0	0.500	785.242	7.892	0.072	15.985
18	200	20.0	0.500	795.242	7.692	0.071	16.2105
19	200	20.0	0.500	765.242	7.672	0.070	16.19
20	200	20.0	0.500	775.242	7.592	0.072	16.305

3. Methodology

3.1 Entropy weight measurement

The objective of Entropy weight measurement method is to determine the weights of each response parameters without any consideration of the decision of decision maker. The character of entropy weight is the higher weight index value more useful than smaller one. The following steps are based on the research suggestion to find the weight index of each response [26-28].

Step I: To evaluate the "*m*" alternatives, from "*n*" attributes, where the alternatives are I_p, T_on, F_p and the attributes are *MRR*, *TWR*, *ROC* and R_a for this particular problem.

Step II: The experimental results are changed in the form of decision matrix, i.e. $M[x_{ij}]_{mxn}$, where *M* is the Decision matrix and x_{ij} is the j^{th} attributes results of the i^{th} alternatives.

Step III: To compare among each response parameters the Decision matrix is normalized by beneficial attribute (i.e. maximum values), and non-beneficial attribute (i.e. minimum values). The Normalized matrix is calculated by using the following mathematical equation.

$$r_{ij} = \frac{x_{ij} - \min(x_{ij})}{max\ (x_{ij}) - min(x_{ij})} \tag{4}$$

$$r_{ij} = \frac{max\ x_{ij} - \min(x_{ij})}{max\ (x_{ij}) - min(x_{ij})} \tag{5}$$

i = 1, 2,…, m and j = 1, 2,…, n

Step IV: After normalization put the value of r_{ij} in the equation (3) to found Nr

$$Nr = (r_{ij})_{mxn} \tag{6}$$

Then, find $S = (S_{ij})_{mxn}$

$$S_{ij} = \frac{r_{ij}}{\sum_{i=1}^{m} r_{ij}} \tag{7}$$

Step V: Calculate the entropy value e_j which represents the entropy evaluation of j^{th} index

$$e_j = -\frac{1}{\ln m}\sum_{i=1}^{m} S_{ij}\ ln\, S_{ij} \tag{8}$$

where i = 1, 2,…, m and j = 1, 2,…, n.

Step VI: Entropy weight W_j of the j^{th} index is determined by the following relation

$$W_j = \frac{1 - e_j}{n - \sum_{j=1}^{n} e_{ij}} \tag{9}$$

3.2 Overall evaluation criteria (OEC)

An overall evaluation criterion (OEC) is a multi-objective optimization technique, where multi characteristics problems combined to give a single numerical index. The objective of this method is to determine the optimum condition based on their overall performance. The individual OEC is analysed by larger the better or smaller the better for easy interpretation. For this purpose *MRR* is consider as larger the better, and *TWR*, *ROC*, R_a are smaller the better. The individual normalized characteristics in OEC are formulated as following:

Larger the better:

$$\text{OEC} = \left[\frac{\text{Value} - \text{Minimum Value}}{\text{Maximum Value} - \text{Minimum Value}}\right] \times \text{weghit of each attribute} \tag{10}$$

Smaller the better:

$$\text{OEC} = 1 - \left[\frac{\text{Value} - \text{Minimum Value}}{\text{Maximum Value} - \text{Minimum Value}}\right] \times \text{weghit of each attribute} \tag{11}$$

The OEC value is calculated by the combine of different machining characteristics to a single index by the following relation, i.e.

$$\begin{aligned} OEC_i = \left[\frac{M_i - M_{min}}{M_{max} - M_{min}}\right] \times W_{mrr} + 1 - \left[\frac{T_i - T_{min}}{T_{max} - T_{min}}\right] \times W_{twr} \\ +1 - \left[\frac{Ro_i - Ro_{min}}{Ro_{max} - Ro_{min}}\right] \times W_{roc} + 1 - \left[\frac{S_i - S_{min}}{S_{max} - S_{min}}\right] \times W_S \end{aligned} \tag{12}$$

where *i, M, T,* R_0 and *S* stands for experimental run order, material removal rate, tool wear rate, radial overcut, surface roughness, respectively. The W_{mrr}, W_{twr}, W_{roc}, W_s are the weight of corresponding responses [9-12].

3.3 Fuzzy logic system

Fuzzy logic concept is introduced by L.A. Zadeh in 1965. This concept turns out with the human common sense reasoning, i.e. the uncertainty decision-making in the situation of problems occurs. It is a multi-reasoning logical concept where the evaluation based on true/false, yes/no and high/low etc. The fuzzy-logic rules are defined in terms of human linguistic like extremely small, very small, small, medium, less high, high, very high, very very high and extremely high etc. In general fuzzy logic involves four basic major ways fuzzifier, knowledge base, inferences engine, and defuzzifier. In fuzzifier each parameters is converted to crisp numerical value. The typical crisp value ranges from 0 to 1. In this parts the specific information of input and output parameter are converted in the form of membership function. This membership function is well set by certain range of boundaries value in the form of fuzzy set and always represented by human language. After the fuzzy set is initialized the knowledge base part defines the input–output membership function by several fuzzy rules. The fuzzy rules are described by the fuzzy set membership function in the form of 'if-then' rules. In the Mamdani fuzzy system the rules are generated in the following ways.

Rule 1: if X_1 is H_1 and X_2 is H_2 and X_3 is H_3 and X_4 is H_4 then Y_1.

Rule 2: if X_1 is H_1 and X_2 is H_2 and X_3 is H_5 and X_4 is H_6 then Y_2.

Rule *n*: if X_1 is H_n and X_2 is H_n and X_3 is H_7 and X_4 is H_8 then Y_n.

where, X_1, X_2, X_3, X_4 are four inputs, H_1, H_2,..., H_n human linguistic parameters and Y_1, Y_2,..., Y_n is the output.

In the inferences engine the fuzzy rules set are constructed based on the behaviour analysis of the combined input–output membership function and decision-making of the operator. Finally the defuzzifier is converts the fuzzy value into a single fuzzy reasoning grade known as multi performance characteristic index (MPCI). For deffiuzation several methods are available but widely used methods namely centroid method. In this paper also this method is used to find the crisp output value. Mathematically centroid or centre of area (COA) method can be expressed as

$$COA = \frac{\int \mu_{\mathrm{F}}(Y)\, Y\, dy}{\int \mu_{\mathrm{F}}(Y)\, dy} \tag{13}$$

where $\mu_F(Y)$ is the output of the *n* rules of the inferences engine and Y_i (i = 1, 2,..., n) are the output variables [19-26].

4. Results and discussion

In the present work, the influence of process parameters has been established in combination of Entropy weight measurement, OEC and fuzzy logic approach. As per the Entropy weight measurement approach, the experimental results are arranged in the form of decision matrix D_{mxn} of the given attributes is shown in Table 2. Furthermore, D_{mxn} matrix is normalized as minimum requirement attributes by Eq. 4 and maximum attributes by Eq. 5. *MRR* is considered as beneficial attribute (i.e. maximum values), while *TWR, ROC and* R_a is considered as non-beneficial (i.e. minimum values). After normalization, the individual weight is evaluated using Eq. 6 to Eq. 9. Weight of each response is shown in Table 3.

Table 3 Weight of each response

Expt. No.	*MRR*	*TWR*	*ROC*	R_a
1	0.244	0.251	0.251	0.254
2	0.245	0.260	0.243	0.252
3	0.256	0.245	0.249	0.251
4	0.252	0.250	0.251	0.247
5	0.238	0.256	0.256	0.250
6	0.248	0.258	0.248	0.246
7	0.259	0.244	0.248	0.249
8	0.257	0.245	0.251	0.247
9	0.248	0.245	0.252	0.254
10	0.251	0.256	0.248	0.246
11	0.238	0.256	0.249	0.256
12	0.265	0.240	0.249	0.247
13	0.249	0.252	0.248	0.251
14	0.252	0.248	0.254	0.246
15	0.249	0.252	0.249	0.250
16	0.249	0.252	0.249	0.250
17	0.249	0.251	0.249	0.250
18	0.249	0.252	0.249	0.250
19	0.249	0.252	0.249	0.250
20	0.249	0.252	0.249	0.250

For multi objective optimization, the OEC approach has been utilized. As per this concept, the individual responses are normalized with implication of weightage of individual responses using Eq. 10 and Eq. 11 as shown in Table 4.

To get better optimal machining parameters the individual normalized OEC of the response is again applied to fuzzy logic technique to find a single numerical index value is known as Multi performance characteristics index (MPCI). In this paper for fuzzy logic model four inputs are consider as the output of the individual normalized OEC of *MRR*, *TWR*, *ROC* and R_a as well as the output parameter be the MPCI as shown in Fig. 1.

In fuzzy logic modelling the input is represented by three linguistic variables likely minimum, medium and maximum for output five linguistic variables such as very small, small, medium, large and very large. The shapes of the membership function are in the form of triangular membership function. By using MATLAB R2007b version, 20 fuzzy logic rules are implementation in the form of 'if-then' control rules with their membership function are executed to find the single numerical index known as MPCI. The result of MPCI and ranked the order based on its largest single numerical index value is shown in Table 5.

Table 4 Normalized OEC of each response

Expt. No	*MRR*	*TWR*	ROC	R_a
1	0.010	0.186	0.136	0.186
2	0.032	0.254	0.000	0.174
3	0.162	0.070	0.102	0.089
4	0.147	0.170	0.070	0.081
5	0.000	0.256	0.256	0.200
6	0.123	0.255	0.195	0.112
7	0.220	0.069	0.093	0.092
8	0.178	0.069	0.041	0.027
9	0.084	0.117	0.165	0.184
10	0.128	0.226	0.049	0.059
11	0.004	0.256	0.204	0.256
12	0.265	0.000	0.033	0.037
13	0.081	0.182	0.037	0.139
14	0.146	0.144	0.208	0.069
15	0.088	0.179	0.110	0.114
16	0.086	0.178	0.119	0.114
17	0.090	0.177	0.106	0.116
18	0.092	0.179	0.110	0.113
19	0.088	0.179	0.114	0.113
20	0.089	0.180	0.106	0.111

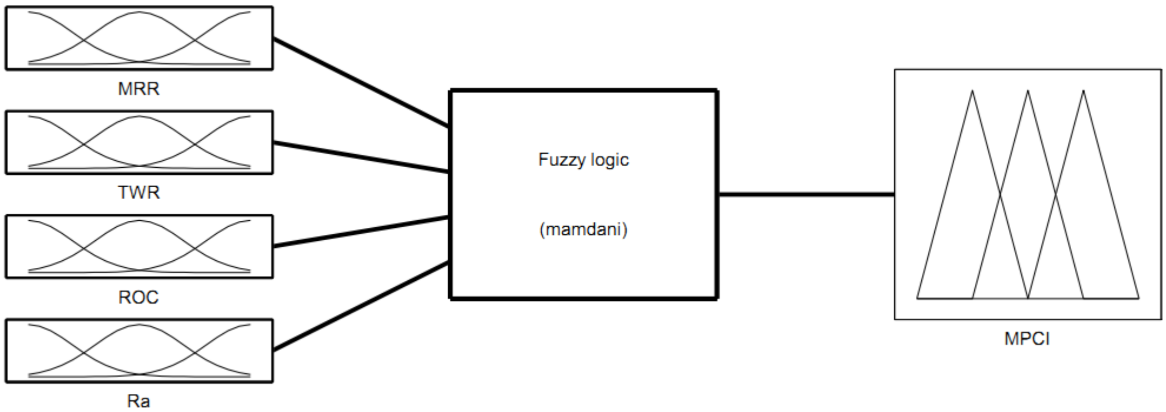

Fig. 1 Fuzzy logic model

Table 5 MPCI of the responses

Expt No	MPCI	Rank order
1	0.3291	20
2	0.5343	8
3	0.5241	9
4	0.5455	7
5	0.5811	5
6	0.7039	2
7	0.6413	3
8	0.5196	10
9	0.4628	11
10	0.4439	12
11	0.7155	1
12	0.6082	4
13	0.3753	19
14	0.5694	6
15	0.4043	16
16	0.4025	18
17	0.4071	14
18	0.4092	13
19	0.4043	17
20	0.4051	15

4.1 Analysis of variance (ANOVA)

ANOVA is a statistically based method to verify any differences in the average performance, when a group of combination of parameters are tested. The results of ANOVA of MPCI are shown in Table 6. If the P-value less than 0.05 then the model terms of response are significant at 95 % of confidence level.

The R^2 and Adj R^2 value are indicating the goodness of fit for the model. If it close to unity the experimental result is better and fit for the model. [30-31]. In the present study, the R^2 value for *MRR, TWR,* R_a and *ROC* are 96.80 %, 98.47 % , 96.80 % and 96.22 %, respectively. Similarly, Adj R^2 value for *MRR*, *TWR*, R_a and *ROC* are 93.92 %, 97.09 %, 93.91 % and 92.81 %, respectively. It indicates that the model shows a better result.

Table 6 ANOVA of MPCI

Source	DF	SeqSS	AdjSS	Adj MS	F	P	Remark
Linear	3	0.055108	0.005658	0.001886	1.76	0.218	Not significant
Square	3	0.129541	0.129541	0.043180	40.34	0.000	Significant
Interaction	3	0.042924	0.042924	0.014308	13.37	0.001	Significant
Residual error	10	0.010705	0.010705	0.001070			
Total	19	0.238277					

4.2 Response surface methodology

Response surface methodology (RSM) is a combination of mathematical and statistical techniques used to build the numerical equation. The primary objective is to make a relationship between the responses and process parameters [30]. The relationship between the machining characteristics is commonly represented by a function Ø

$$Y = \emptyset\ (T_{on}, I_p, F_P) \tag{14}$$

where Y is defined as the response, T_{on} is pulse on time, I_p is Peak current, and F_p is flushing pressure of dielectric.

The second order mathematical model (quadratic model equation) for response is represent by

$$\begin{aligned} Y = \beta_0 + \beta_1 T_{on} + \beta_2 I_p + \beta_3 F_P + \beta_4 T_{on}{}^2 + \beta_5 I_p{}^2 + \beta_6 F_p{}^2 \\ + \beta_7 T_{on} \times I_p + \beta_8 T_{on} \times F_p + \beta_9 I_p \times F_p \end{aligned} \tag{15}$$

where β_0 is the constant. β_1,..., β_3 , β_4,..., β_6, and β_7,..., β_9 are coefficients of linear, square and interaction terms, respectively. As per the Eq. 15 the mathematical equation for MPCI is developed as given below

$$\begin{aligned} MPCI = 0.132819 + 0.000769 T_{on} - 0.006205 I_p + 0.636178 F_P \\ + 0.000008 T_{on}{}^2 + 0.00093 I_p{}^2 + 0.647885 F_p{}^2 \\ - 0.000107\, T_{on} \times I_p - 0.002819\, T_{on} \times F_p - 0.020644\, I_p \times F_p \end{aligned} \tag{16}$$

5. Confirmation test

The confirmation test has been conducted with the highest rank of MPCI value, i.e. the run order 11 as shown in Table 5. The corresponding process parameter for highest rank of MPCI is T_{on} = 200 µs, I_p = 3.2 A and F_p = 0.500 kg/cm^2. The optimum set of process parameter is put into the Eq. 16 of RSM model to predict the response (MPCI). It has been found the overall percentage of error is very small with its experimental and predicted values as shown in Table 7. As a result the qualities of multiple machining characteristics are improved by selecting these process parameters.

Table 7 Compression result between highest MPCI

Numerical index	Parameters setting on the basis of highest MPCI	Predicted results	Experimental results	% of error
MPCI	T_{on} = 200 µs I_p = 3.2 A F_p = 0.500 kg/cm^2	0.6929	0.7155	3.262

6. Conclusion

In the present study, the multi objective optimization techniques are used to find out the optimal set of process parameter for machining of Al-24 % SiCp MMC in EDM. The experiments are conducted with central composite design of experiments. Al-24 % SiCp MMC is machined with three input variables viz. peak current, pulse on time and flushing pressure to obtain the *MRR*, *TWR*, *ROC* and R_a as response variable.

Based on the experimental and analytical result following conclusions are drawn:

- The proposed methodologies like Entropy weight, OEC and fuzzy logic are easy and promising technique to convert the multi-objective characteristics into single numerical index known as multi performance characteristics index (MPCI). The highest rank of MPCI predicts the optimum set of combination of process parameter for machining of Al-24 % SiCp MMC in EDM.

- The ANOVA is used to analyse the significance MPCI model terms and it is found the square & interaction terms are significant one whereas the liner term is insignificant.
- The second-order mathematical model is developed for predicted MPCI value by using RSM.
- Finally the confirmation test is carried out to verify the percentage of overall error and it has been found that the error is 3.262 %.
- The present approach provides a good agreement with the experimental and predicted value of response which improves the quality of machining of Al-24 % SiCp MMC in EDM.

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