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Investigation of Heat Transfer Performance of Shell and Tube Heat Exchanger

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Abstract- Objective of this research is to investigate the heat transfer performance of STHE (Shell and Tube Heat Exchanger). For this purpose, STHE with baffles and without baffles have been modelled in MATLAB Simulink, by using its block diagrams. Simulink models have been developed by using NTU (Number of Transfer Units) effectiveness method. Both models are verified mathematically by using NTU effectiveness heat transfer equations. Heat transfer and outlet temperature of cold fluid are achieved at different inlet temperature of hot fluid. Reference value of inlet temperature of hot fluid is set at 500, 480, 460, 440 and 420 °C and different values of heat transfer and outlet temperature of cold fluid are achieved. After that, comparisons between baffles and without baffles model have been developed for STHE performance. Greater heat is transferred in baffles model instead of other without baffles model at same inlet conditions. Cold fluid outlet temperature is better in baffles model instead of without baffles model. Moreover, a non-linear direct relationship is found between inlet temperature of hot fluid and outlet temperature of the cold fluid. Heat transfer rate is decreased by decreasing the inlet temperature of hot fluid. Hence, this research proves that baffles or cross flow shell and tube heat exchangers gives the batter heat transfer as compare to counter flow STHE.

Keywords-Shell and Tube Heat Exchanger, MATLAB Simulink, NTU, Transfer Function, Fluid Flow Rate, Fluid Temperature, Heat Transfer

I. INTRODUCTION

1.1. Introduction to Heat Exchanger

Heat exchanger is used for transfer of heat from one fluid to another at various temperatures. The fluids may be a liquid or a gas [1]. Many type of heat exchangers are used for the heat transfer but mostly STHE is being used. More than 90% of the industries are being used STHE [2]. A STHE has bundle of tubes in a cylindrical shell. The tubes may be fixed or may be removable. It is universally used for non-compact duties and can also be used for high temperature and pressure applications [3]

1.2. MATLAB/Simulink

MATLAB is a language for practical computing. It integrates the visualization, computation and programming in an usable background where solutions and problems are stated in aware mathematical system [4]. It is also used in several applications such as communication, problem solving, control design and numerical analysis [5]. Simulink is the modules of MATLAB, it has block diagram library for model based design and simulation. It supports automatic code generation, design, simulation, continuous test and verification of embedded systems [6]. In Simulink, the block diagrams are directly used for mathematical equations and get results with different input parameters[7].

1.3. Heat transfer methods

Log Mean Temperature Difference (LMTD) method is a technique used to find the heat transfer performance at different inlet outlet conditions of the STHE. Whereas Number of Transfer Units (NTU) effectiveness method is also used to find the heat transfer of the STHE. In LMTD method heat transfer cannot be found without the knowledge of outlet conditions. But in effectiveness method heat transfer can be calculated without any prior knowledge of the outlet conditions[8].

II. GOALS AND OBJECTIVES

The goal of this research is to Investigation the heat transfer performance of STHE using MATLAB Simulink. For this purpose, a system is designed with different type of configuration to calculate the heat transfer of STHE. The aims of the research are follows:
1. Specify boundary conditions of models.
2. Mathematical equations are modelled by using NTU

method in MATLAB Simulink..
3. Models are verified theoretically.
4. Modify the models with different configuration to find the heat transfer performance at different inlet/outlet temperature conditions.

III. Literature Review

Castell et al, Fakheri et al and Selbas et al have been found the transfer of heat in heat exchanger using LMTD approach. This method is not effective because the transfer of heat and effectiveness of STHE cannot be found without the knowledge of outlet condition of the fluid[9-11]. Garcia uses NTU effectiveness method for modelling of heat transfer system while the heat exchanger is working as evaporators or condensers. This model is used for pre-assignment and correct selection of STHE in complex and full refrigeration systems –[12]. Green and Tassou have been used the NTU method for mathematical modelling of shell and tube condenser in refrigeration applications [13]. Dobos et al have been developed dynamic model of heating system for shell and tube heat exchanger. New heat exchanger is developed by using these equations and modeled them in MATLAB Simulink[14]. Costiuc developed the model of heat exchanger in Simulink and it is used as the component of refrigeration system. This research is helpful for designing and the analysis of a refrigeration system before its functional optimization and physical existence[15]. Hardik et al, Ghorbani et al and Alimoradi have been developed the relationship between NTU free and mixed convection for this purpose modelled a helically coiled tube heat exchanger in Simulink. This model is analysed its Reynolds and Rayleigh numbers and geometrical parameters[16-18].
Pavlusova uses the block diagram from the library of MATLAB Simulink to develop the model of heating system[19]. Heat transfer rate increased by using fins spacing geometry for heat sink of microprocessor comparative to flat surface. It have been observed that with the decrease of fin spacing heat transfer rate increases using water as cold fluid. [22]. Heat transfer performance could be improved by using Graphene Nano platelet mixing with water as compared to distilled water as heat exchanging fluid [23-24].
Heat exchange behaviour is observed using micro-hole cellular structure. It is found that thermal performance could be improved using water cooled cellular structure [25]. Rate of heat transfer of car radiator could be improved by using nanoparticles of ZnO of various concentration in the water as cooling medium. [26]

IV. Methodology

4.1. Materials of Shell and Tube Heat Exchanger

Shell and tube heat exchangers are mostly made up of metals such as copper, mild steel and brass. Typical metals include stainless steel, copper alloy, carbon steel, Inconel, nickel, non-ferrous copper alloy and titanium. Fluoro polymers such as Fluorinated ethylene propylene (FEP) and Perfluoroalkoxy alkane (PFA) are also used to produce the tubing material. Poor selection of tube material could cause the leakage and also causing fluid cross-contamination, probably loss of pressure. Copper piping systems delivers clean and safe domestic water, both hot and cold for drinking. Copper has many properties for durability and thermally efficiency of heat exchangers. Furthermore, it has good conductive property which is good to pass through the heat at wide range of temperature difference. Copper has good other important properties such as high stress against pressure, good corrosion resistance and easy to fabrication purpose.
So, that copper is used as a tube material in STHE because main purpose of this research is heat transfer. Its thermal conductivity is 398 W/m.K[20, 21].

4.2. Configurations of Shell and Tube Heat Exchanger

According to flow configuration STHE has three types of flow configurations namely; parallel, counter and cross flow configuration. [15]
Parallel and counter flow configurations are the less useful arrangement. The Fig. 1(a) shows the parallel flow configuration and Fig. 2(a) show the counter flow configuration.

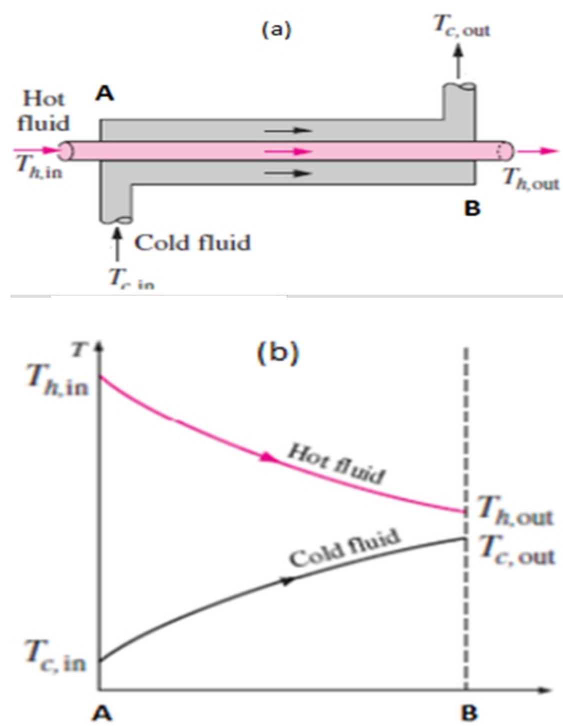

Figure 1: Parallel Flow Configurations of Shell and Tube

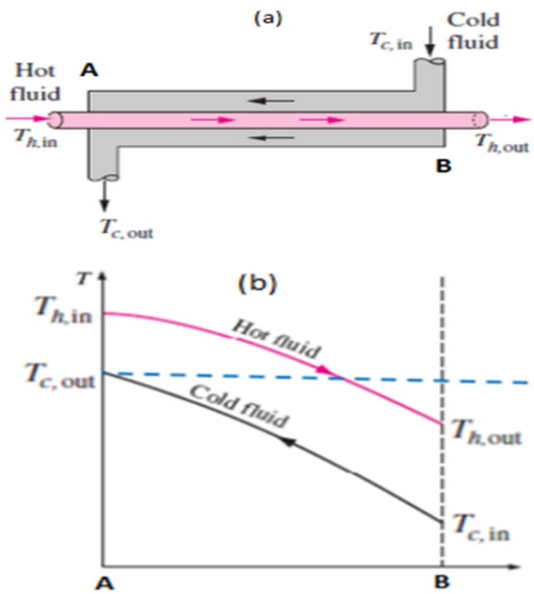

Figure 2: Counter Flow Configurations of Shell and Tube

Fig. 1(b) and Fig. 2(b) are shown the temperature gradient. In Fig. 2(b) shows the greater temperature gradient as compare to Fig. 1(b).

In cross flow configuration baffles are included due to these baffles flow in shell side crosses the tubes which creates turbulence. In general, where the flow is turbulent more heat is transferred as compare to parallel and counter flow, so this is preferred. Fig. 3 shows the cross flow configuration.

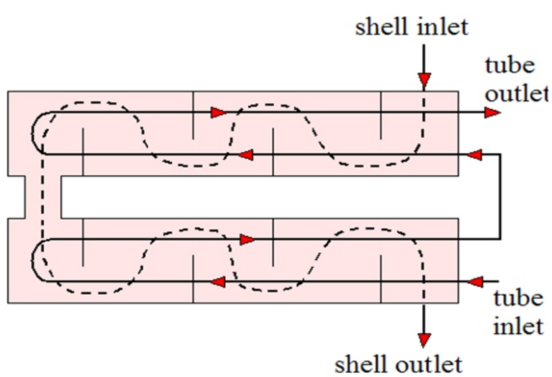

Figure 3: Cross Flow Configuration

According to flow arrangement, it may be in different arrangements such as single shell, single tube, multi shell and multi tube. In single shell single tube arrangement flow is laminar and little heat is transferred in this arrangement. In multi tube arrangement, baffles are added for turbulence effect and tube strength. Here in this research, the single shell and single tube is used in initial stage for parallel and counter flow configuration. For cross flow configuration; multi tube and single shell with baffles arrangement is used in shell and tube heat exchanger.

Nomenclature used is described in Table 1:

Symbols	**Description**	**Units**
Q_c	Heat Transfer of cold Fluid	W
Q_h	Heat Transfer of cold Fluid	W
C_{ph}	Specific heat of hot fluid	J/kgK
C_{pc}	Specific heat of cold fluid	kJ/kgK
U	Overall heat transfer coefficient	W/m^2K
A	Surface area	m^2
t	Tube thickness	mm
r	Tube radius	cm
l	Tube length	m
D	Tube diameter	cm
T_{hin}	Hot fluid inlet temperature	^0C
T_{hout}	Hot fluid outlet temperature	^0C
T_{cin}	Cold fluid inlet temperature	^0C
T_{cout}	Cold fluid outlet temperature	^0C
T_{tin}	Tube side inlet temperature	^0C
T_{tout}	Tube side outlet temperature	^0C
T_{sin}	Shell side inlet temperature	^0C
Re	Reynolds number	--
Pr	Prandtl Number	--
N_{uD}	Nusselt Number	--
f	Darcy Friction Fact	--
ε	Effectiveness	--
V	Velocity	m/s
μ	Dynamic viscosity	Ns/m^2
υ	Kinematic Viscosity	m^2/s
ρ	Density	Kg/m^3
Cmin	Minimum heat capacity	W/K
C_{max}	Maximum heat capacity	W/K
m_c	Mass flow rate of cold fluid	kg/s
m_h	Mass flow rate of hot fluid	kg/s
h_{gas}	Thermal connectivity of gas	W/m^2K
k_{tube}	Thermal conductivity of tube	W/mK
h_{water}	Thermal conductivity of water	W/m^2K

4.3. NTU Effectiveness Method of Heat Transfer

NTU method is used to determine the effectiveness and outlet temperatures. In such conditions, the heat transfer can be calculated by a guess of outlet temperatures by using equations 1, 2 and 3 [15].

$$Q_h = C_h \Delta T_h = C_h \left(T_{h_{in}} - T_{h_{out}} \right) \quad (1)$$

$$Q_c = C_c \Delta T_c = C_c \left(T_{c_{out}} - T_{c_{in}} \right) \quad (2)$$

$$Q_c = Q_h = C_c \Delta T_c = C_h \Delta T_h \quad (3)$$

The heat exchanger effectiveness is defined as, The processes being followed consist of the machining of ceiling body and plate, motor's stator wining and fitting. Process flow analysis (PFA) is a powerful tool for quantifying material travel distance, WIPs, no of workers and value-adding times against each activity. Moreover, the time study technique was used to calculate cycle time (CT) of each activity and then standard time after adding allowances as per the process requirements. This data helped in developing line balancing graph for the whole process. the time study technique was used to calculate cycle time (CT) of each activity and then standard time after adding allowances as per the process requirements. This data helped in developing line balancing graph for the whole process.

III. Validation Case Study

To validate the proposed lean implementation method for SMEs, a case study was developed. A medium sized company, employing around 200 personnel was selected for this purpose. The above-mentioned framework has been followed as a lean implementation strategy, further explanation and effectiveness of the adopted methods have been discussed in the proceeding sections. The implementation process took around 9 months; starting from goal setting to formalizing key lessons learned during the whole process. A key element of this approach, as discussed was the involvement of stakeholders especially employees and management where special attention was given to the suggestions forwarded by the employees during the decision making process. the time study technique was used to calculate cycle time (CT) of each activity and then standard time after adding allowances as per the process requirements.

3.1. Setting goals and the establishment of KPIs

As a first step, our team shared the objective with the management of the company and constituted a steering committee responsible for follow up of the whole process. The committee was covering a broad range of employees representing different work groups; for example representative of top management, managers, production and quality related shop floor employees, health and safety, human resource, finance etc. so that wider wisdom could be captured. However, the majority of the members were from design, production and quality departments. The team set a goal for productivity improvement through designing interventions against the following KPIs:

- Reduction in Work-In-Process
- The decrease in Batch Travel Distance
- Increase in Average Production per Day
- Improvement in Line Balancing Efficiency
- The decrease in the Number of Workers

3.2. Performance evaluation of current practices, data collection and data analysis

Existing work practices were evaluated against the set KPIs by using a number of commonly practiced tools and techniques like process flow analysis, spaghetti diagram, value stream mapping, cause and effect diagram, Pareto analysis, 5S and time study. The company produces three different types of fans, namely, ceiling, pedestal and bracket and louvre with 69%, 22% and 9% of overall production respectively. Four sections of ceiling production line were selected for the activity. Process flow charts of the selected activities are shown in Fig. 2.

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The PFA summary shown in Table 1 displays that 45 workers produce a lot of 600 pieces per day, where value-added time is 1005 seconds per piece and material travel distance is more than 26KM per day. Surprisingly, Work in Process (WIP) is over 8000 means an average inventory of about 14 days is stuck on the production floor. The layout of fan manufacturing industry is usually designed on the basis of processes rather than products; therefore the high value of material travelling distances has been witnessed in table 1. Additionally, production processes have not synchronized those results in more temporary storage places. The current layout of body machining and fitting is shown in Fig. 3 below. For the purpose of developing line balancing graph, the following values have been used: Start time (8 am); End time (5 pm); Total hours per day (9); No of breaks (1); Working hours per day (8 hours, 480 minutes and 28800 seconds). Previous data was used to understand variations in production demands and Takt time (working time / monthly demand) calculations were made accordingly. Three monthly demand values (15000, 22500, and 30000 pieces per month) were used to find Takt time (48, 32 and 24 sec/pc) respectively. Three options were generated in view of the current and future demand as forecasted by the factory management. TAKT time is a dynamic function which will vary corresponding to the demand in hand. However, existing demand value of 22500 pieces per month, with 45 workers were used to develop a line balancing graph shown in Fig. 4, which clearly identifies the bottleneck operations in plate, body, stator and fitting operations.

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3.3. Development of an interventions implementation plan

As the implementation framework is mainly based on the active participation of employees and top management in the decision-making process. So the investigations were shared with the stakeholders and they were requested to help out in designing practically feasible low-cost interventions so that these could be implemented easily. Focus group discussions were made with the representatives where they shared their ideas about the improvements in the performance. This helped in capturing a diverse pool of suggestions for improvements against the highlighted bottlenecks. Later on, all suggested interventions were analyzed by a team of experts and their conclusions were shared with the employees so that they could learn about other ideas and enrich their knowledge about the work practices and their relationship with production performance.

As a starting point, the production demand was fixed at 22500 pieces per month and TAKT time calculated accordingly (32 seconds per piece). This step helped in determining resources required to match the requirements. To improve the line balance efficiency, ECRS technique was applied to balance the load on workers by Eliminating the unnecessary processes (E), Combining of processes (C), Rearranging the processes (R), and Simplifying the processes (S). A strategic change in the policy of working hours was made where the shift time was raised from 8 hours to 9.5 hours in order to satisfy the demand of 22500 pieces. Importantly, this change was brought after having deliberated discussions with the workers, this increased the TAKT time from 32 to 38 seconds. Process requirements and material handling requirements were found to be critical in this respect and new plans were developed accordingly. Another major intervention suggested and implemented was to change the layout from process layout to product layout. This helped in ensuring a proper sequence of operations eliminating sources of contaminations, difficult to access areas and practices curtaining the flow of production. This improved the travel distance from 26145 meters to 3680 meters. The new sample layout of the fitting shop and line balancing diagram after interventions is Fig. 6 and 7.

Additionally, workers were trained on new procedures so that standardized work practices could be promoted. They were made aware of health and safety, well-being and work ergonomics-related issues and their implications for productivity. Workers were given the opportunities to share their views on lean implementation and how these issues could be addressed so that the sustainability of interventions could be ensured. This helped in promoting a healthy work environment where management and workers were ready to play their role in adopting a cultural change towards lean thinking.

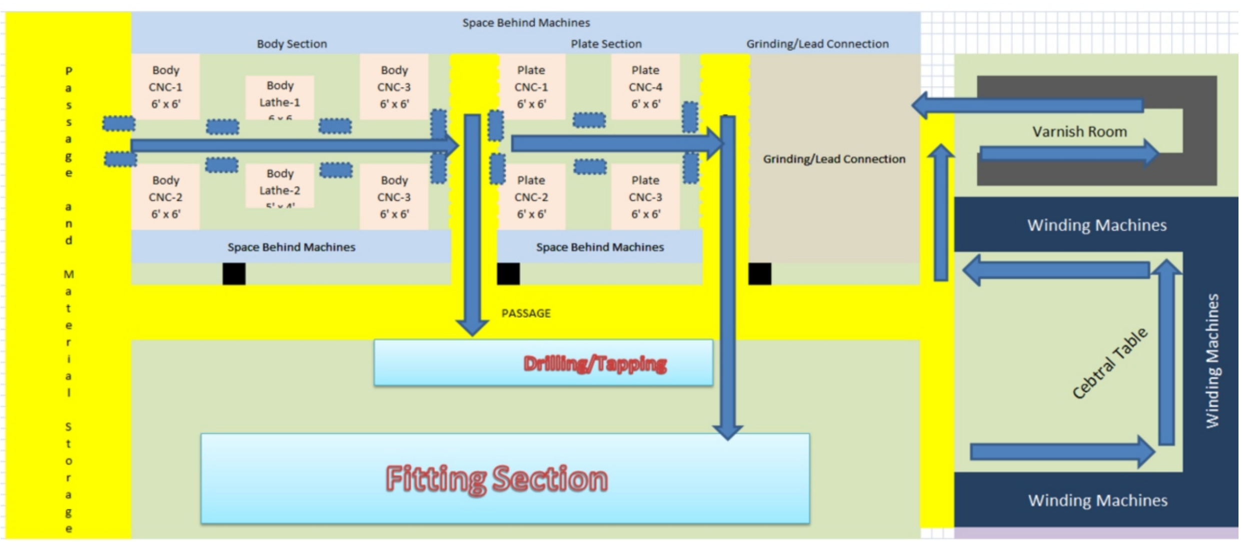

Fig. 6 New layout of the fitting shop (after)

Fig. 7 Line balancing graph (after)

Table 2 Percentage Improvement

Parameters	Before	After	Percentage Improvement
WIP (pieces)	8374	3000	64
Batch Travel Distance (meters)	26145	3680	86
Average Production per Day (pcs/day)	666	922	38
Line Balancing Efficiency (%)	36	84	133
No of Workers	45	35	22

3.4 Reassessment of KPIs and lessons learned

Key performance indicators mentioned previously were calculated again and comparison was made. Fig. 8 concludes the improvements made against each KPI. During this whole process of lean implementation strategies, it has been keenly observed that participation of employees is a good source of information for developing cost-effective intervention plans for improvement. Work performance investigation and standardization tools like time study, Pareto analysis, line balancing, ECRS etc. have been found very much useful. Being part of the process, workers showed a gesture of ownership that helped in the development and implementation of cost-effective ideas in a sustainable manner. It's concluded that the process of lean tools implementation can be made easier by following the proposed systematic approach.

IV. DISCUSSION

Adoption of 'Lean Strategy' leads towards cost reduction and value addition for customers through quality improvement and hence helps organizations to be competitive in the market [24, 25, 26, 27]. As far as the implementation of lean is concerned, it has to focus areas: one is lean philosophy whereas the second one is related to tools, techniques and their successful implementation processes and procedures [28, 29]. Achievement of desired objectives and goals through lean implementation could be made sustainable through organizational cultural change, where the behaviour of employees in terms of their roles and responsibilities are highly important [30, 31]. Employees' perceptions about Lean implementation have been a point of discussion in literature as both positive and negative perceptions exist at the same time

[31]. To overcome implementation challenges, the participatory approach could be used to increase employee's opportunities to be the part of the decision-making process that is most likely to increase the level of innovation, sense of support, ownership, control and well-being at work [32, 33].

In light of the above discussion, the challenge of successful implementation of Lean could be achieved through the use of participatory interventions approach. The proposed participatory based systematic lean implementation approach has been found useful for investigating work performance related issues and then designing and implementation of low-cost interventions. The case study presented proved that the use of lean tools in combination with the participatory approach is an effective technique for the effective utilization of human capital for bringing a positive cultural change in organizations. The effectiveness of the participatory approach is established; however, its application for the purpose of successful implementation of lean tools has been investigated and found useful [32, 33]. This shows a substantial potential for improving cost competitiveness of SMEs by using lean tools in combination with the participatory approach. Participation of employees continually helps in designing low-cost interventions which are usually the need of SMEs. Hence the employees which are the part of lean implementation process could be instrumental in the sustainability of applied interventions and designing of new ideas for future improvements.

Hence, for overcoming lean implementation barriers, the proposed participatory based framework is an effective approach for lean culture transformation. This approach is based on the effective engagement of stakeholders especially employees at all stages of implementation process. Involvement of employees help in understanding the problem in more realistic way, devising strategies to overcome problems, generating more diverse kind of solution ideas and most importantly ownership of changes being made. The framework is a continuous improvement cyclic process that can help organizations in achieving their long term goals.

Implementation of lean is required long term management commitment that requires resources and time in addition to the promotion of awareness and understanding through trainings. Implementation strategy proposed in this study is a way forward for managers to learn from the experience of how to engage employees positively. Similarly, some common issues related to productivity and quality improvement have been investigated where effectiveness of suggested interventions have been reported. These findings could help managers in developing customized solutions as per the requirements of their own systems.

V. CONCLUSIONS

Promotion of 'Lean Thinking' is linked with organizational cultural change. Small and Medium Enterprises (SMEs) encounter challenges like high implementation cost and employees' ownership. These barriers could be eliminated through the promotion of the participatory approach for implementing low-cost interventions. This study proposed a participatory-based lean implementation methodology for SMEs, which is a 7-steps cyclic approach that can help in promoting a lean culture in the organization. Validation of the framework has been done through a case study in the manufacturing industry. It is concluded that participation of stakeholders especially employees is a highly useful method for the design and implementation of low-cost interventions by using different lean tools like process-flow analysis, line balancing, time study, Work-In-Process (WIP), Pareto analysis etc. Identified KPIs have been measured at pre and post interventions stages. Results indicate promising improvements in terms of reduction in batch travel distance (86%), decrease in work-in-process (64%), increase in average production per day (38%) and a decrease in a number of workers (22%). It is concluded that the development and implementation of low-cost interventions through active participation of employees, during the process of lean implementation, can significantly improve the process performance, which ultimately leads to achieving cost competitiveness in SMEs.

VI. LIMITATIONS AND FUTURE RESEARCH

The scope of this case study has been the implementation of lean practices at one production line in a fan manufacturing company due to time and resource constraints. Future research may increase the scope of such initiatives at multiple manufacturing concerns and industrial sub-sectors where key lessons learned like the validation of participatory approach for lean implementation, role of employees' engagement and improvement strategies against set KPIs could be used in future research. Substantial time had to invest on creating awareness and orientation on lean practices among the owners and employees of the company. In addition, insufficient commitment on part of the top management, inadequate resource planning, panic to transform, work burden, lacking inclusive and participatory approach to develop continuous improvement culture have been the limiting factors observed during implementations of this productivity improvement initiative.

Due to the absence of performance management system, collection of reliable data had been a major challenge as the development and monitoring of productivity related KPIs is directly linked with this.

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