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Research article

Leveraging Optimized and Cleaner Production through Industry 4.0

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ABSTRACT

Manufacturing sector has traditionally employed the concepts of lean manufacturing for production optimization and waste elimination. However, the looming danger of climate change demands responsible production and consumption; oftentimes the environmental aspects have been ignored for economic gains. The fourth industrial revolution brought about a paradigm shift in the manufacturing landscape, yet there is dearth of approaches that combine the concepts of lean manufacturing, environmentally conscious manufacturing and Industry 4.0 for improving the production and ecological performance of manufacturing sector. This study has fulfilled this research gap by developing a comprehensive implementation framework that combines lean manufacturing, green manufacturing and Industry 4.0 in a harmonious manner. Using a longitudinal case study approach, the developed framework has been applied to an auto-parts manufacturing firm to achieve reduced lead time, value added time, non-value-added time and greenhouse gases (GHG) emissions. The results revealed that the approaches of first-in-first out (FIFO), total productive maintenance (TPM), smart production control, cyberphysical systems, 6R and smart energy monitoring are extremely beneficial in achieving optimized and cleaner production, where the lead time, non-value added time and value added time has been reduced by 25.60%, 56.20% and 24.68% respectively, whereas the carbon dioxide, methane and nitrous oxide emissions were reduced by 55%. The theoretical contribution of this research work lies in the development of a novel integration framework that combines the concepts of lean manufacturing and green manufacturing with Industry 4.0 technologies, whereas practitioners can benefit from the synergistic combination to achieve automation-based fast and environmentally conscious manufacturing.

1. Introduction

The manufacturing sector carries immense significance in contributing towards the economic development of a country, since it acts as a potential lever for poverty amelioration and providing decent work to skilled, semi-skilled and even unskilled labour. However, the economic progress has come at a dear cost of environmental deterioration i.e. too often the ecological performance of the sector has been compromised for economic gains. This negligence has culminated in the testing challenge of climate change, where the temperatures across the globe are on the rise. Therefore, the current challenge is three-fold is nature i.e. improving the performance of manufacturing sector without compromising on the environmental paradigms, whilst employing contemporary manufacturing techniques. The fourth industrial revolution, formally known as Industry 4.0 presents an interesting opportunity to tackle both issues. However, on a broader scale, it is necessary to uphold the triple bottom line of sustainability in which the social, economic and environmental performance of manufacturing systems are ensured in a harmonious manner.

In order to ensure the economic sustainability of a manufacturing setup, lean manufacturing has always helped in improving the production performance by eliminating the manufacturing wastes i.e. defects, over-production, waiting time, under-utilized labour, transportation, inventory, motion and extra-processing (Lacerda et al., 2016). Used profusely in the management of manufacturing systems (Moyano-Fuentes and Sacristán-Díaz, 2012), the concepts of lean are applicable in the services sector as well (Ganesh, 2020, Gupta and Sharma, 2016). Lean can be viewed as a philosophy (Bhasin and Burcher, 2006) that has overarching applications in supply chain (Khorasani et al., 2020). The application of lean concepts reduces the lead time and non-value-added time of the manufacturing process, however the concept of JIT is detrimental to the environmental performance (Mollenkopf et al., 2010), which begs the question: is lean necessarily green? (Venkat and Wakeland, 2006). Therefore, adoption of green manufacturing approaches is of vital importance in as-

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surance of improved social and environmental sustainability of a manufacturing process (Deif, 2011); and it is necessary to integrate environment friendly practices in the manufacturing strategy (Govindan et al., 2015). Green manufacturing carries a broad meaning, and it can be hypothesized that it involves reduction of wastes, reduction in GHG emissions (Pang and Zhang, 2019), reduced energy consumption (Leong et al., 2019), performing lifecycle assessment (Reich-Weiser et al., 2010) and reducing carbon footprint (Bhattacharya et al., 2015). Jayal et al. (2010) propose the adoption of 6R approach i.e. reuse, reduce, recycle, recover, redesign and remanufacture which ensures reduced energy and resource usage at the manufacturing stage. The adoption of green approaches is not merely limited to manufacturing; business processes adopt green practices as well to develop a sustainable enterprise (Vom Brocke et al., 2012). However, a strong coordination between the members of supply chain is necessary to achieve holistic greenness (de Sousa Jabbour et al., 2015).

In order to achieve increased coordination between the supply chain members, the technologies associated with Industry 4.0 are of vital importance. Dubey et al. (2016) assert the importance of BigData analytics and suggest that it strongly drives organizations towards world class sustainable manufacturing, whereas Belhadi et al. (2020) suggest that it positively influences the environmental performance. In the extant literature, there has not been a consensus on what forms Industry 4.0 where some researchers suggest that it comprises of more than 50 technologies (Klingenberg et al., 2019). However, a few common technologies occurring in the literature include BigData, Internet of Things, RFID, Artificial Intelligence, Machine Learning, Additive Manufacturing, Integrated Systems, Cyber-physical systems, Cloud Computing, 3D Printing, etc. The machinery used in Industry 4.0 differs from conventional machinery in the sense that it employs the use of cyberphysical systems with Human-Machine-Interface, that records the data and uses machine learning to record past behaviours. Such machines communicate with each other using cloud and are connected to Internet of Things where real time data is collected and analysed (Rojko, 2017), and these technologies assert the dominance of Industry 4.0 over the conventional technologies (Frank et al., 2019).

In spite of the fact that there has been a vast majority of work carried out on exploring the interrelationships of lean manufacturing, green manufacturing and Industry 4.0; there exists a requirement of a framework-based approach that combines the three paradigms in an harmonious manner to achieve optimized production and environmental performance. The concepts of lean and green have been integrated before in construction sector (Banawi and Bilec, 2014), business models (Duarte and Cruz-Machado, 2013), manufacturing sector (Thanki et al., 2016, Abreu et al., 2017, Mittal et al., 2016) and supply chain (Bortolini et al., 2016, Cherrafi et al., 2018). Similarly, lean manufacturing has been integrated with Industry 4.0 technologies (Kolberg and Zühlke, 2015, Mrugalska and Wyrwicka, 2017, Sanders et al., 2016). The concepts of green manufacturing have been discussed in Industry 4.0 context (de Sousa Jabbour et al., 2018, Belhadi et al., 2020) however there is no such approach that combines the three domains using an integration framework. Machado et al. (2020) performed a systematic literature review regarding sustainable manufacturing opportunities in an Industry 4.0 environment, but the research work exhorts the researchers to develop an implementation tool. In line with the caveat present in the literature, the authors have formulated two research questions:

RQ-1. How can the concepts of lean manufacturing and green manufacturing be combined with pertinent Industry 4.0 technologies for implementation in manufacturing sector?

RQ-2. What economic and environmental benefits can be achieved by the synergistic implementation of lean manufacturing, green manufacturing and pertinent Industry 4.0 technologies?

In line with the research questions, the authors have developed a comprehensive implementation framework, which fulfils the requirement of an integrated approach that combines lean and green manufacturing with relevant Industry 4.0 approaches. The framework has been developed by using the process improvement methodology present in the extant literature. Upon implementation of the framework in an auto-parts manufacturing firm, an improvement in production and ecological performance was observed, which will be extremely useful to operations and manufacturing management practitioners. The paper is structured as follows, Section 2 gives an overview of the current state of the art and elicits a research gap, Section 3 concerns the methods and framework development, Section 4 discusses the results of the implementation of framework on a manufacturing facility, Section 5 discusses the results whereas Section 6 concludes the research work and proposes directions for future research.

2. Literature Review

It is an established fact that manufacturing sector is a strong driver of productivity growth, which offers extensive employment opportunities to the labour force of a country. In order to achieve positive and sustainable economic performance, it is imperative to adopt best practices in the manufacturing sector. Sustainable manufacturing aims towards developing a manufacturing system in which there is minimization of environmental impacts, conservation of natural resources and energy, the produced goods are safe for employees, communities and consumers and are economically sound (Dubey et al., 2015). In order to ensure high economic performance, the concept of lean manufacturing has been discussed in the literature and various implementation frameworks have been developed. Mostafa et al. (2013) developed a generic framework for lean manufacturing implementation which was divided into four phases. Rafique et al. (2017) developed a technology combined lean implementation framework that harnesses the strength of RFID, which is one of the constituent technologies of Industry 4.0. The lean tools of 5S, TPM, VSM, Andon, Kanban, Jidoka, Heijunka, etc. strongly influence the operational performance of a manufacturing unit, whereas the concept of JIT (just-in-time) delivery is a strong driver of efficient supply chain. However, lean principles do not offer eco-efficiency, in fact the JIT approach strongly contributes to the environmentally detrimental GHG emissions. Therefore, the multi-faceted challenge requires the manufacturing sector to adopt sustainable manufacturing approaches where the economic, environmental and social dimensions of sustainability are catered to in a holistic manner. In order to achieve environmental sustainability, the green manufacturing approach serves as a handy tool as it enables reduction of hazardous emissions and ensures sustainable consumption and production (Deif, 2011).

The fourth industrial revolution or Industry 4.0 brought about a paradigm shift in the manufacturing landscape, where the conventional approaches are replaced with smart and intelligent systems. In the extant literature, there has not been a consensus on what forms Industry 4.0 where some researchers suggest that it comprises of more than 50 technologies (Klingenberg et al., 2019). However, a few common technologies occurring in the literature include BigData, Internet of Things, RFID, Artificial Intelligence, Machine Learning, Additive Manufacturing, Integrated Systems, Cyber-physical systems, Cloud Computing, 3D Printing, etc. In this technologically intensive environment, the opportunities for sustainable development are rife. Kamble et al. (2020) investigated the relationship between sustainable operational performance, lean manufacturing and Industry 4.0 technologies and suggested that the lean manufacturing practices strongly influence the adoption of Industry 4.0 technologies, such as BigData analytics, cloud computing and IoT. Therefore, it can be said that lean implementation is a precursor to smooth Industry 4.0 adoption. Ghobakhloo (2020) has employed interpretive structural modelling technique to investigate relationships between Industry 4.0 technologies and sustainability, concluding that digital technologies such as IIoT, AVR, robotics, cloud computing, etc. are at the centre of digital transformation which offers opportunities for economic development. Similarly, the environmental sustainability aspect of Industry 4.0 technologies has been discussed in the literature as well; Belhadi et al. (2020) have discussed the relationships between BigData analytics and environmental performance, positing that BigData acts as a great lever for improvement of environmental performance. Likewise, Mao et al. (2019) have discussed the impact of artificial intelligence on green manufacturing, suggesting that artificial intelligence helps in ensuring process safety and reduced energy consumption, an idea supported by Wu et al. (2019).

The authors posit that an integrated approach is necessary to uphold the triple bottom line of sustainability with Industry 4.0 technologies. On an integration level, there have been several frameworks that combine the concepts of lean and green manufacturing in a systematic manner. Sawhney et al. (2007) put forward the idea of environmental lean (En-Lean) in which the framework was divided into four phases which included development of En-Lean matrix, industrial data collection and its analysis, which culminates in the development of an interface; subsequently applied to a metal cutting industry. However, the research work did not discuss the results of the selected framework in terms of production improvement and environmental performance. Farias et al. (2019) developed a conceptual framework that uses various lean practices such as 5S, VSM, SMED, Kaizen, etc. and links them with green practices such as LCA, 3R, environmental management system, etc. Despite that, the framework lacked practical application through a case study-based approach. A conceptual model was developed by Dües et al. (2013) regarding the intersection of lean and green paradigms, however the practical implications of the research work remain to be seen. Maqbool et al. (2019) have developed an integration framework that combines lean manufacturing with the concept of 6R, consequently implemented on a metal part manufacturing firm to achieve favourable results.

Similarly, the idea of Industry 4.0 and lean manufacturing integration via a framework is still in its nascent stages. Ghobakhloo (2018) present a roadmap for Industry 4.0 however it has been based upon empirical evidence gathered from previous research works. The introduction of Industry 4.0 principles in a lean manufacturing environment makes the processes efficient, resulting in better economic performance by waste reduction. Sony (2018) suggests that lean manufacturing can aid in achieving horizontal, vertical and end to end integration and presents an integration framework, however it is general in nature and needs to be elaborated further for effective implementation. James and Cervantes (2019) have used a case study approach to integrate lean manufacturing with Industry 4.0 technologies, subsequently applied to an aerospace manufacturing firm using Arena simulation modeling tool. Similarly, the concept of green manufacturing and Industry 4.0 integration has not been explored at a framework level.

It is therefore incumbent to consolidate a comprehensive framework of such nature that its implementation is not an arduous task. Duarte and Cruz-Machado (2017) have discussed the possibility of integrating lean, green and Industry 4.0 concept in supply chain context but that remains a conceptual model. Kamble et al. (2018) presented a framework to achieve sustainability by implementing Industry 4.0 concepts of BigData and smart manufacturing, but the research work lacks practical validation. Therefore, at present, there is no research work that offers a comprehensive integration framework combining lean manufacturing, green manufacturing and Industry 4.0 concepts; a crevice that needs to be filled.

3. Methods

3.1. Framework Design

After confirmation of the research gap in Section 2, the authors have developed a holistic framework that combines the approaches of lean manufacturing, green manufacturing and pertinent Industry 4.0 technologies. Being a process improvement framework in its innate nature, the developed framework takes inspiration from the work of Mast et al. (2000) who suggest that the basic tenets of any process improvement framework include planning, analysis, improvement and control phases. Prashar (2016) suggest that the process improvement frameworks follow should require statistical process control whilst harnessing the potential of DMAIC methodology. Since the fundamental aim of this study is to develop a framework that will consequently be applied to a manufacturing firm using case study-based approach; the authors have not only utilized the work of Mast et al. (2000), but have consulted previous literature in selecting the phases and steps of the framework. The research works of Bhamu and Sangwan (2016), McLean and Antony (2017) and Rafique et al. (2017) were helpful in designing the framework. The steps and phases have been meticulously selected after extensive deliberation, given below in Table 1.

The six phases and twenty-seven steps of the framework given in Table 1 and Fig. 3 are explained below:

3.1.1. Phase 1 – Lean Conceptual Phase

This is the commencement phase of the production optimization process in which the product line is subjected to the principles of lean manufacturing to reduce wastes. After extensive literature analysis, it has been observed that in order to introduce lean manufacturing, it is necessary to familiarize the organizational personnel with the benefits of lean manufacturing. The steps are given as follows:

- Identify the problems faced by the industry e.g. unable to meet customer demands, too much overtime by the workers, late product deliveries, etc. Problems of such nature have a great impact upon manufacturing and organizational performance. Once these problems have been identified, there should abe a general consensus (constancy of purpose) among the management to eradicate the issues.
- It is necessary to introduce lean philosophy and its benefits to the workers and management personnel to ensure that everyone fully understands the concepts; which if simply stated, is elimination of waste.
- The organization should move towards building a lean team which should include a Board Member, Production Manager, Production Team and General Manager.
- After identifying the problems, the lean knowledge should be instilled amongst the involved personnel to ensure that the definition of waste is clear. Moreover, the terminologies of cycle time, lead time, takt time, changeover time, etc. should be explained.

3.1.2. Phase 2 – Lean Preparation Phase

After due compliance by the organizational personnel, the next step is to make necessary preparations for commencing lean activity. The steps are:

Table 1
Steps & Phases of Implementation Framework.

Phase Title	Steps Required	Reference from Previous Literature
Lean Conceptual Phase	1. Identify the problems faced by the industry 2. Introduce Lean Philosophy 3. Build a Lean Team 4. Impart Lean Knowledge	Nordin et al. (2010), Poppendieck and Poppendieck (2013), Kreimeier et al. (2014), Rafique et al. (2017) Bhamu and Singh Sangwan (2014), Kreimeier et al. (2014)
Lean Preparation Phase	1. Careful selection of product family 2. Perform “Go to Gemba” Walk 3. Identify the problems	Singh et al. (2010), V. Ramesh (2008), Wilson (2010)
Lean Implementation Phase	1. Draft Current State Map 2. Identify Wastes 3. Introduce a Pull System 4. Subjecting Material to Flow	Kreimeier et al. (2014), Wahab et al. (2013), Soltan and Mostafa (2015), Das et al. (2014)
	5. Identify areas for smart production control and automation	Zawadzki and Żywicki (2016), Gjeldum (2016), Buer et al. (2018), Rüttimann and Stöckli (2016), Satoglu et al. (2018)
	6. Introduce Stability 7. Propose Future State Map	Rafique et al. (2017), Wilson (2010), Anand and Kodali (2010)
	8. Check Validity through Simulations	Mohamed A. Shararah (2011), Doğan and Unutulmaz (2014),
Lean Completion Phase	1. Transformation as per Future State Map	Anvari et al. (2011)
	2. Introduce Smart Production Control & Cyberphysical Systems using Industry 4.0	Kolberg and Zühlke (2015), Tortorella and Fettermann (2017), Mrugalska and Wyrwicka (2017)
	3. Propose Implementation Plans	Wilson (2010), Gupta and Jain (2013), Vienažindienė and Čiarnienė (2013)
	4. Build Lean Organization	Koenigsaecker and Taha (2012), Yoskovitz (2013), Ţenescu and Teodorescu (2014)
	5. Continuous Improvement	Soltan and Mostafa (2015), Barbosa et al. (2014)
Green Preparation Phase	1. Introduce concepts of Green Manufacturing	Deif (2011), Lee (2008), Bergmiller and McCright (
	2. Top Management Commitment	K. Digalwar et al. (2013), Zhu et al. (2010)
Green Implementation Phase	1. Implement ISO 14001 & Reduce GHG Emissions	Farias et al. (2019), Pang and Zhang (2019), Baumer-Cardoso et al. (2020)
	2. Implement 6R technique	Jayal et al. (2010), Jawahir and Bradley (2016), Maqbool et al. (2019)
	3. Use renewable energy resources 4. Implement energy efficient practices	Garbie (2016), Paul et al. (2014), Leong et al. (2019)
	5. Smart Factories with energy monitoring (using Industry 4.0)	Frank et al. (2019), Mohamed et al. (2019)

ANOVA						
Source of Variation	*SS*	*df*	*MS*	*F*	*P-value*	*F crit*
Between Groups	1.6368017	1	1.636802	0.000872993	0.976530208	4.006872886
Within Groups	108746.03	58	1874.932			
Total	108747.67	59				

Fig. 1. ANOVA Results of Current State Map.

- Identification of the product family in which the major problems occur. Major product family is selected based on maximum number of operations involved and maximum revenue generation. As for product family, two production lines would be considered a part of same product family if they have 80% similar operations (Duggan, 2013).
- After identification of product family, Go-To-Gemba-Walk should be performed in which real time data from shop floor is to be collected, that helps in the drafting of current state map.

3.1.3. Phase 3 – Lean Implementation Phase

Value stream mapping is an extremely powerful tool which enables users to get a clear view of the processes and the resources consumed, therefore it is used in the implementation of lean manufacturing principles. The steps of lean implementation are given as follows:

- Drafting of current state map in which each process is observed carefully from the context of cycle time, lead time, changeover time, value added time and number of operators involved. This is extremely useful in identifying the production wastes.
- The production performance should be in-line with the customer demand, therefore a pull system is necessary; in which the production is subjected to a flow without the requirement of an external agency (push) in the production (except in case of supermarkets)
- Using the concepts of Industry 4.0, the tools of Smart Production Control and Cyberphysical System must be used to increase

ANOVA						
Source of Variation	*SS*	*df*	*MS*	*F*	*P-value*	*F crit*
Between Groups	6.983682	1	6.983682	0.015448	0.901516	4.006873
Within Groups	26220.63	58	452.0798			
Total	26227.61	59				

Fig. 2. ANOVA Results of Future State Map.

the process efficiency. This will lead to a flexible manufacturing system where high-end customization can be achieved through automation.
- Future State Map should contain all the modifications discussed above and should be drafted based on the eight lean questions. Kaizen blitz is a powerful tool to propose changes in the process.
- Once drafted, the future state map should be verified using simulation software to ensure the changes are practical.

3.1.4. Phase 4 – Lean Completion Phase

After the future state map has been verified using simulations, the production should be transformed as per; whilst employing smart production control & cyberphysical systems. Continuous improvement is a key facet in this context, and once the organization has achieved leanness, it should continue to make itself better.

3.1.5. Phase 5 – Green Preparation Phase

Green manufacturing is synonymous to environmentally conscious manufacturing in which the whole manufacturing process focuses on reducing emissions and environmental wastes. The steps in preparing an organization for green manufacturing are given as under:

- The organization should be introduced to the concepts of green manufacturing. It is of paramount importance to educate people regarding the adverse effects of toxic emissions, non-recyclable materials and pollution.
- The top management must keep green manufacturing in their view, the policies and strategies should be made as per.

3.1.6. Phase 6 – Green Implementation Phase

After educating, the implementation phase commences which includes the following steps:

- Implementation of ISO 14001 protocols which suggest the use of environmental management system to enhance the environmental performance. It provides a framework through which an organization can manage short term and long-term environmental goals, reduce costs, reduce wastes and improve the resource efficiency. It is important to be cognizant of the GHG emissions produced by the manufacturing process.
- Use of 6R techniques, which are summarized as follows:
  - i Reduce the use of material and resources i.e. optimize the system
  - ii Reuse the products by working towards extension of product life
  - iii Remanufacture products using reused and repaired parts
  - iv Recycle the products by using environment friendly recyclable material
  - v Recover products by enhancing their lifecycle
  - vi Redesign the product in such a manner that it follows the aforementioned
- Instead of using fossil fuel resources, there should be a gradual shift towards renewable energy resources, as per the industry requirements. In manufacturing environment, the use of solar panels and skylights is highly feasible
- Smart energy monitoring should be implicated, in line with machinery maintenance, so power consumption does not exceed a certain threshold.

3.2. Rationale for Case Study

Customarily the research in operations management has been based on quantitative approach, since it is proclaimed that qualitative research lacks the rigor and objectivity of its counterpart (Patton and Appelbaum, 2003, Yin, 1981). However, in order to develop a clear picture of a phenomenon during in-depth examination, case study is a handy approach (McCutcheon and Meredith, 1993), but requires theoretical development. In quantitative research, the survey based approach helps in dealing with the research phenomenon, however it has been observed survey carries a limited ability to deal with the research context (Yin, 2017). Since operational and manufacturing management research demands a delicate balance between research phenomenon and research context, therefore case study approach seems the most appropriate. Moreover, Yin (2017) states that case study approach can build upon the previous theoretical development. After developing the framework, the authors sought to test it by implementing it on a real-world case, thus the use of longitudinal case study approach was deemed the most appropriate as it allows to study change (Demeter et al., 2020, Rajagopalan, 2020).

4. Results

4.1. Framework Implementation

In order to implement and validate the developed framework, the authors have used a case study-based approach in which data was collected from an automotive parts manufacturing company, SSZ Group (pseudonym used for confidentiality reasons) that produces axles and hardware, engine parts, shock absorber parts, hardware and high precision products for local and international vendors. SSZ's top management is committed to quality (ISO 9001 certified) and has a proper corporate governance structure in practice. The major products of the company, in the descending order of revenue generation, are given as follows:

- Product PS-01 & PS-02 for 70cc & 125cc Motorcycles (150,000 pieces per month)
- Product SC-01 for Motorcycles (65,000 pieces per month)
- Product BF for Motorcycles (85,000 pieces per month)

4.1.1. Lean Conceptual Phase

Even though the facility is one of the market leaders in production of motorcycle and tractor parts, it was observed that there has been difficulty in meeting customer demands within the stipulated time; therefore, the facility must work overtime. The company's top management was cognizant of the issues at hand and the authors worked closely with the top management and relevant production personnel for gap analysis, data collection, and proposing a process improvement plan. Thus, the authors visited the facility to perform a comprehensive analysis of the processes and identify the

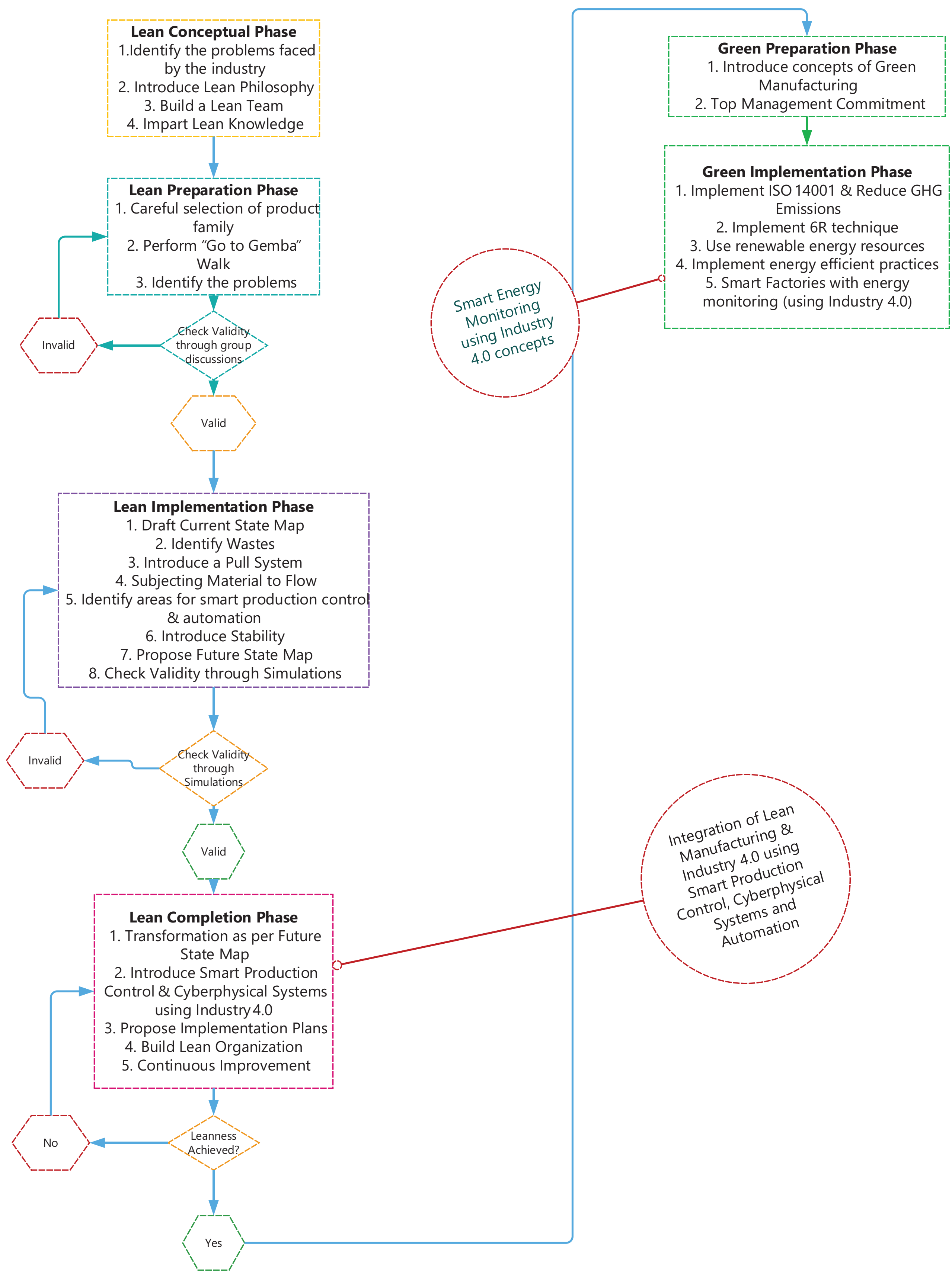

Fig. 3. Industry 4.0 based implementation framework for integrating lean and green manufacturing.

causes of lower production rates. The implementation commenced with the introduction of lean concepts to the manufacturing facility, and a lean-green team was proposed that would enact the production optimization and ecological improvement suggestions.

4.1.2. Lean Preparation Phase

The authors selected the PS product family and, in that family, Product PS-01 manufactured for 70cc bikes were selected. The data was collected through field observations, followed by process mapping of whole production process. Gemba walk was performed in presence of Assistant Manager Production (AMP) and the processes were studied in detail. In case of 70cc Product PS-01s, a total of 25 processes are currently in practice from raw material cutting to final packaging, involving a workforce of 29 personnel. Proceeding further, a project team was proposed for implementing the framework; which would include production, maintenance, safety and environment, quality assurance and IT personnel. After selection of product family, the processes- from raw material arrival to final delivery -were visualized along with the information flow to consolidate the current state map. The following data were collected:

- Orders for customers are received on monthly basis, and the supplier is intimated accordingly
- Total available working time
- Total parts produced per day
- Number of machines and operators involved
- Total value added time & non-value added in each operation
- Total cycle time
- Production lead time

During the Gemba walk and time study, it was observed that there is excess of waiting and motion by the workers. The major issues are summarized below:

- The product is subjected to over motion due to bad layouts, which needs to be addressed
- Instead of moving with one-piece flow, the operators are using excessive inventory (400 pieces' lot)
- The product is subjected to over-processing because of low First Time Quality percentages
- There is a lack of automation among the processes, which presents a safety hazard as well
- The machinery needs to be multi-functional so that similar processes can be clubbed

4.1.3. Lean Implementation Phase

The third phase of the implementation framework commenced with drafting of the current state map of the selected product family. After these observations, the current state map was generated as per (Rother and Shook, 2003). Each production process was minutely observed in terms of number of machines, number of employees, cycle time of each machine, changeover time of each machine and the WIP inventory; which categorizes as non-value added time. In the present scenario, the SSZ Group uses inventory of 400 pieces in each process. Furthermore, the following general data was collected in terms of one-piece flow, given in Table 2:

The current state map was validated using a simulation software, in order to check the consistency and authenticity of the registered values for cycle time. The simulation was run for one-piece flow with 30 replications and the values were compared by using Analysis of Variance (ANOVA) (Rafique et al., 2017). In accordance with the concepts of Industry 4.0, it was analyzed that the manufacturing process needs to be controlled via a cloud-based system which provides real time visibility. The collected data, alongwith the proposed changes is given in the Table 3.

For the case of SSZ Group, the major wastes included inventory, motion, waiting and defects. In addition to these wastes, there were frequent machinery breakdowns that caused production delays. This necessitated the use of TPM as per lean principles. The process was subjected to a pull system, which in essence is a customer driven concept where the production is determined by the customer demand. The takt time was calculated (7.97 secs) and supermarkets were used in packaging process. Moreover, Smart Production Control was used to automate and integrate scheduling with production planning, using the concept of Internet of Things (Zawadzki and Żywicki, 2016).

The production line was subjected to FIFO, so that the waste of inventory can be eradicated. The pacemaker process was defined, and it was scheduled by Smart Production Control, which helped in adjusting the production capacity according to the demand fluctuation. The following major improvements were made, as seen in Table 3:

- Installation of conveyor belt from blank cutting machine to blank chamfering machine so that FIFO can be achieved.
- Automation of Grooving, Finishing & Turning Operation: Manual operation took almost twice the amount of time as compared to automatic operation; and the production was one-thirds in comparison to automatic process. Therefore, it was advised to make the process completely automated.
- Automation of Ø6.8mm Drilling Operation: Manual operation took almost thrice the amount of time as compared to automatic operation; and the production was one-thirds in comparison to automatic process. Therefore, it was advised to make the process completely automated.
- Re-drilling of holes was due to bur removal, which was reduced by using a drill bit integrated with a retractable deburring cutter.
- The machinery was equipped with power factor improvement appliances so that electricity could be conserved.
- Instead of 30 day supply & delivery period, SSZ Group adopted biweekly delivery schedule to mitigate the risks that arise due to socio-political changes or natural disasters (Bhamra et al., 2011).

The current state map was validated using a Simulation software, in order to check the consistency and authenticity of the registered values for cycle time. The simulation was run for one-piece flow with 30 replications and the values were compared by using Analysis of Variance (ANOVA) (Rafique et al., 2017). The hypothesis was accepted or rejected based on the significance level assumption of 0.05. The null hypothesis (H_0) stated that simulated values and actual cycle time values of the plant do not significantly differ, whereas the alternate hypothesis (H_1) suggested that the actual and simulated values differ significantly. Therefore, if the value of P achieved was greater than 0.05, H_0 became true and if the value was less than 0.05, H_1 became true. The tests were run for one-piece flow and the value of P was found out to be 0.9765, which validated the null hypothesis H_0 and confirmed that the values do not differ significantly.

- H_0= Simulated values and actual values do not differ significantly
- H_1= Simulated values and actual values differ significantly
- Significance: $P>0.05$

The authors based the concept of future state map generation upon the rules stipulated by Rother and Shook (2003) and followed by Abdulmalek and Rajgopal (2007). The simulation and validation practices were iterated in future state map as well, and the cycle times were compared using ANOVA for single piece flow. The hypotheses are given as follows:

- H_0= Simulated values and actual values do not differ significantly

Table 2
General Production Data.

Data	Measured Value
Size of order received from customer	85,800 pieces
Total Lead Time	62 days, 17 hours, 3 minutes and 12 seconds
Total Available Working Time	26,100 seconds
Shifts per day	01
Value Added Time	41.14 minutes
Non-Value-Added Time	1,172.50 minutes
Average Cycle Time	1212.90 minutes
Total Number of Operators Involved	31
Total Number of Machines Involved	26
Total Number of Processes	25

- H_1= Simulated values and actual values differ significantly
- Significance: P>0.05

The value of P came out to be 0.9015, which is significantly greater than 0.05, thus validating the null hypothesis that values do not differ significantly.

4.1.4. Lean Completion Phase

Since lean manufacturing is considered to be the precursor of successful implementation of Industry 4.0 technologies, therefore the proposed future state map was integrated with pertinent Industry 4.0 technologies. A cloud based production control system was proposed that harnesses the potential of sensors and RFID tags for increased visibility. At the same time, the laborious process of chemical treatment was subjected to a robotic-arm based cyber-physical system in order to ensure health and safety of the worker.

4.1.5. Green Preparation Phase

After successful implementation of lean manufacturing, the authors proposed the adoption of green manufacturing techniques, as the latter is complemented by the predecessor (King and Lenox, 2001). The lean-green team was educated regarding the concepts of environmentally benign manufacturing, and it was essential for the top management to be involved in this process.

4.1.6. Green Implementation Phase

In this phase, the company adopted ISO 14001 standard and decided to lower their greenhouse gases emissions. In the manufacturing processes, the concept of 6R was introduced and renewable energy sources were explored. On an organizational level, energy efficient practices were adopted in which the power factor of the machinery was improved to lower the electricity consumption, while skylights were proposed to reduced the lighting load. Moreover, smart energy monitoring was proposed using Industry 4.0 principles in which the electricity consumption statistics were recorded and analyzed using BigData analytics. It is pertinent to mention that green manufacturing implementation is an iterative process and requires perseverance and unerring commitment.

4.2. Improved Production Performance

4.2.1. Reduction in Lead Time

It was observed that overall lead time was reduced by 25.60% by following the proposed future state map, as shown in Fig. 4.

The delivery time was reduced from 30 days to a fortnightly delivery schedule to accommodate the socio-political risks, in line with the resilient supply chain narrative (Carvalho et al., 2012, Tummala and Schoenherr, 2008). However, the supply time was not been changed from 30 days for safety stock to mitigate the risks (Sheffi and Jr, 2005, Jüttner, 2005).

4.2.2. Reduction in Non-Value-Added Time

Previously, the non-value-added time was 1,172.50 minutes, which was reduced to 525 minutes, thus 55.62% reduction (as shown in Fig. 5), by taking the following measures:

- Using FIFO throughout the process except for chemical treatment and packaging
- Reducing the machinery changeover times as per the process to ensure smooth process flow. However according to the process nature, the changeover times were changed to accommodate worker and machinery rest time.

4.2.3. Reduction in Value Added Time

Previously, the value-added time was 41.14 minutes, which was reduced to 30.99 minutes, thus 24.68% reduction (as shown in Fig. 6), by taking the following measures:

- Reduction in the blank cutting time through consolidated TPM implementation on the cutting machine
- Eliminating the manual processes and increasing the performance of automatic machinery through implementation of TPM, resulting in decreased times
- Integrating the deburring processes with drilling processes
- Reducing the chemical treatment time using pickling additives/catalysts to accelerate the process
- Using automated packaging machine to guarantee exact number of products in single pack

4.3. Improved Ecological Performance

The reduced working hours and implementation of energy efficient practices resulted in significant reduction in the GHG emissions. The emissions statistics against 1 kWh (1 unit) electricity consumption are 0.615374995 kg CO_2/kWh, 0.0000180 kgCH_4/kWh & 0.0000031 kgN_2O/kWh (Khan and Siddiqui, 2017). Previously, the cycle time was 1,213 minutes, which was reduced to 556 minutes therefore it contributed significantly to the reduction in electricity related GHG emissions related to the manufacturing process. Moreover, the number of processes were reduced from 25 to 20, thereby the energy consumption statistics were lowered. As the emission constants vary significantly, therefore logarithmic scale has been utilized for the comparison, as shown in Fig. 7.

Moreover, the solar energy was utilized in the form of skylights to reduce the reliance on industrial lamps, which added to the reduction in energy utilization. Table 3 shows that the green manufacturing practices are not only related to the GHG reduction but encompass the workplace health and safety as well. Issues such as noise reduction and operator safety are paramount in ensuring smooth production, without negatively affecting the worker.

5. Discussion

The research work undertaken in this manuscript sought to explore two objectives: (a) articulate an integration between lean

Table 3
Production & ecological improvements through combined application of Lean Manufacturing, Green Manufacturing & Industry 4.0 (C/T: Cycle Time, COT: Changeover Time).

Sr#	Process	Number of Workers	C/T (secs)	COT (mins)	Proposed Number of Workers	Proposed C/T (seconds)	Proposed COT (minutes)	Lean Manufacturing Approach	Green Manufacturing Approach	Industry 4.0 Approach
Current State					Future State					
1	Cutting of Blanks	3	119.00	120.00	1	95.20	60.00	FIFO & TPM	Reduced energy consumption	• Smart production control • Automated transfer • Smart energy monitoring via cloud control
2	Chamfering of Blanks	1	0.40	17.00	1	0.40	15.00	FIFO & TPM	Noise reduction	• Smart production control
3	Drilling	1	4.00	50.00	1	4.00	25.00	FIFO & TPM	• 6R • Operator Safety	• Smart energy monitoring via cloud control
4	Knob Drilling	1	1.60	40.00	1	1.60	20.00	FIFO & TPM	• 6R • Operator Safety	
5	Cold Forging 1	1	2.50	20.00	1	2.50	10.00	FIFO & TPM	• Noise reduction	• Cyberphysical system for workpiece handling
6	Cold Forging 2	1	3.30	25.00	1	3.30	15.00	FIFO & TPM	• Operator safety	• Smart production control • Smart energy monitoring via cloud control
7	Grooving Facing & Turning (Automatic)	2	7.90	60.00	1	7.11	30.00	FIFO & TPM	Energy efficient machinery	• Sensor based quality checking • Smart production control • Smart energy monitoring via cloud control
8	Grooving Facing & Turning (Manual)	1	18.80	60.00	*Process Eliminated*					
9	Ø6.8mm & Ø3.65mm Hole Drilling (Automatic)	1	10.80	90.00	1	12.64	45.00	FIFO & TPM		• Sensor based quality checking • Smart production control • Smart energy monitoring via cloud control
10	Ø6.8mm & Ø3.75mm Hole Drilling (Manual)	2	34.20	240.00	*Process Eliminated*					
11	Thread Side Drilling	1	6.60	45.00	1	6.60	20.00	FIFO & TPM	Reduced energy consumption through power factor improvement	• Sensor based quality checking • Smart production control • Smart energy monitoring via cloud control
12	Head Side Drilling	1	5.00	40.00	1	5.00	20.00	FIFO & TPM		
13	Thread Side Chamfering	1	6.70	15.00	1	6.70	10.00	FIFO & TPM		
14	Tapping	1	12.10	90.00	1	12.10	45.00	FIFO & TPM		
15	Washing	1	120.00	15.00	1	90.00	10.00	FIFO & TPM	Reusing the washing oil after filtering	-
16	Countersinking	1	6.80	60.00	1	6.80	30.00	FIFO & TPM	Reduced energy consumption through power factor improvement	• Sensor based quality checking • Smart production control • Smart energy monitoring via cloud control
17	Drilling of Ø1.2mm Hole	1	7.30	90.00	1	9.49	45.00	FIFO & TPM		
18	Burr removal of Ø3.65mm Hole	1	13.50	90.00	*Process Eliminated*					
19	Countersinking Cup Side	1	10.30	80.00	1	10.30	40.00	FIFO & TPM	6R	• Sensor based quality checking • Smart production control • Smart energy monitoring via cloud control
20	Grinding	2	5.50	105.00	1	5.50	45.00	FIFO & TPM	6R	
21	Burr removal Ø1.2mm Hole	1	6.00	-	*Process Eliminated*					
22	Burr removal Ø6.85mm Hole	1	6.00	-	*Process Eliminated*					
23	Face Grinding	1	5.90	50.00	1	5.90	25.00	FIFO & TPM	Energy efficient machinery	• Sensor based quality checking • Smart production control • Smart energy monitoring via cloud control
24	PT-5 Chemical Treatment	3	1,980.00	27.00	1	1,500.00	10.00		ISO 14001 Implementation	Cyberphysical system for safe material handling
25	Packing	3	74.00	6.00	1	74.00	5.00	Supermarket		Cyberphysical system for material packaging

manufacturing practices, green manufacturing practices and Industry 4.0 technologies and (b) understanding the economic and environmental impact of the combined implementation of the aforementioned approaches. In order to address RQ-1, the authors have explored the literature on implementation of lean and green manufacturing practices, and using the process improvement models developed by Mast et al. (2000) and Prashar (2016), a comprehensive integration framework was developed. The framework has been divided into six phases (four for lean implementation and two for green manufacturing implementation) and both lean and green approaches have been integrated with relevant Industry 4.0 technologies such as smart production control, cyberphysical systems, smart energy monitoring, automation, BigData analytics, etc.

In order to address RQ-2, the authors have undertaken a simulation-based implementation of the developed framework in the context of an auto-parts manufacturing firm to achieve favourable results. The GHG emissions from manufacturing were reduced by 54.16%, whereas the lead time, value added time and

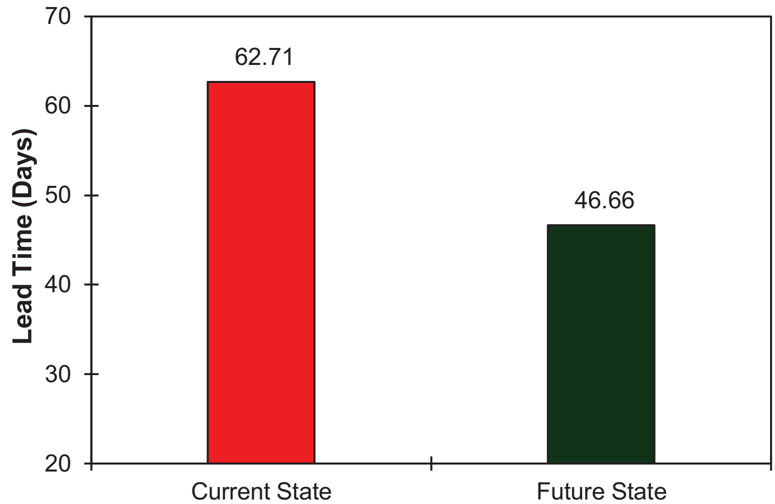

Fig. 4. Comparison of Lead Time: 25.60% reduction by using lean manufacturing techniques and reducing delivery time.

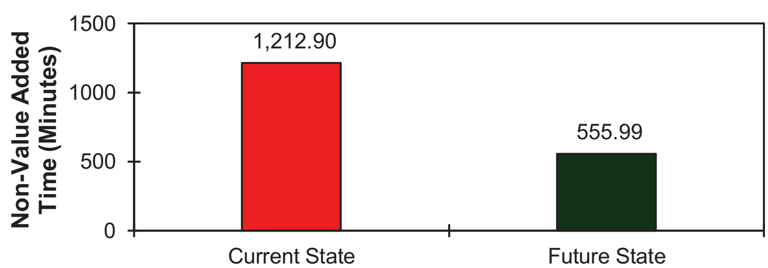

Fig. 5. Reduction in non-value-added time by 56. 2% by eliminating the WIP inventory and reducing machinery changeover times.

non-value-added time were reduced by 25.60%, 24.68% and 55.62% respectively. It was observed that the Industry 4.0 technologies of smart production control, cyberphysical systems, automation and smart energy monitoring complement the improvement in production and ecological performances of a manufacturing process. The improvement in environmental performance is in line with the works of Lee (2013), Cai et al. (2019) and Gielen and Moriguchi (2002). Similarly, the improvement in production process using Industry 4.0 concepts is in agreement with the results of RFID based lean implementation by Tabanli and Ertay (2013), cycle time reduction results by Seth* and Gupta (2005) and lead time reduction results by Maqbool et al. (2019) and Siva et al. (2020). The contribution of this research work is of dual nature i.e. it provides a comprehensive implementation framework for integration

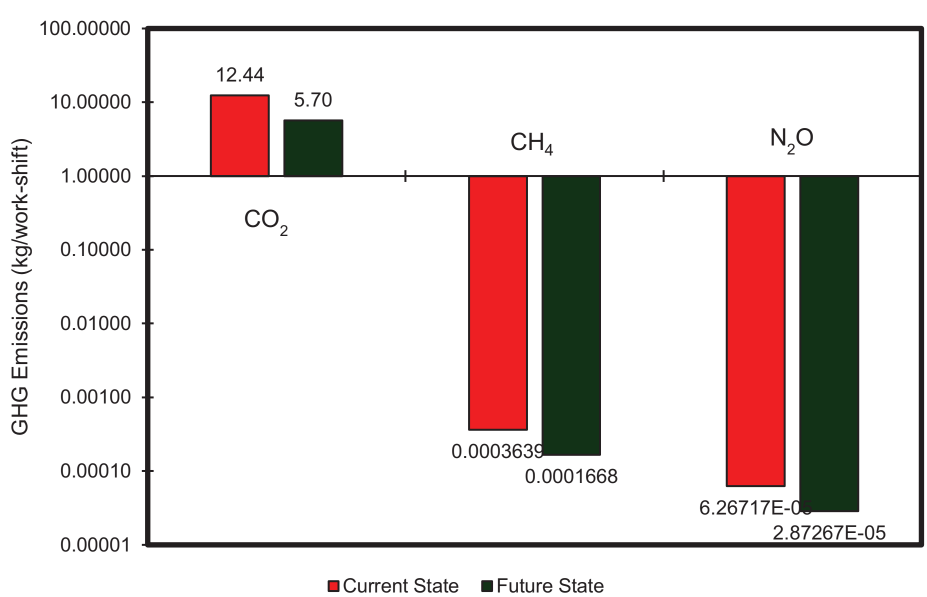

Fig. 7. Comparison of ecological performance of manufacturing process in current state and future state map using logarithmic scale. The emissions have been reduced by approximately 55% per work-shift due to smart energy monitoring, improvement in machinery performance and 6R approach.

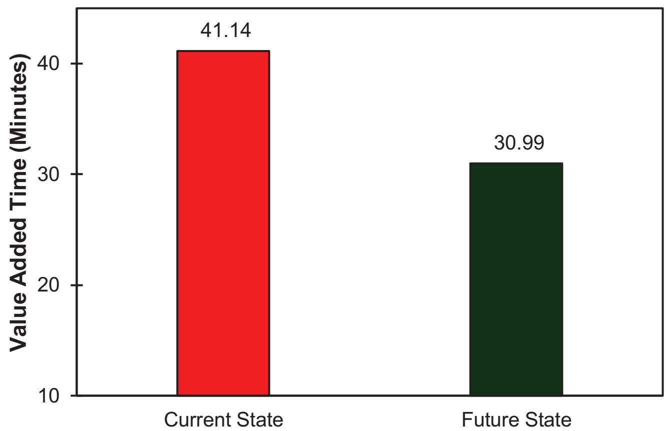

Fig. 6. Reduction in value added time by 24.68% by using FIFO approaches, improving machinery performance using TPM & automation.

of lean manufacturing, green manufacturing and Industry 4.0; and it applies it to a case study to achieve favourable results. Therefore, the research work carries immense practical implications and will surely help practitioners in adopting the discussed approaches.

5.1. Theoretical Contributions

The idea of Industry 4.0 technologies and their sustainability implications have been generously discussed in the literature of the past two years. Researchers have posited that adoption of Industry 4.0 technologies strongly influences the economic pillar of sustainability, whilst having overarching relationship with the environmental and social aspects. Lean manufacturing is considered to be a strong driver for economic sustainability, whereas green manufacturing leverages social and environmental aspects of sustainability. However, the integration of two approaches in an Industry 4.0 environment was missing in the literature, and the integration framework developed in this research work fulfills that research gap. The authors have combined the two approaches in a seamless manner to optimize production and environmental performance of the manufacturing organization, whilst employing relevant Industry 4.0 technologies. It can be said with confidence that the success of adoption of green practices is contingent upon the successful implementation of lean manufacturing. Lean manufacturing also positively influences the application of Industry 4.0 technologies. To the best of authors' knowledge, there is no such framework currently present that combines lean manufacturing, green manufacturing and Industry 4.0 technologies. Therefore, the research work is novel in nature and carries practical significance. The favorable results and easy-to-implement framework will help practitioners in adopting the framework, which will result in improved economic and environmental performance.

5.2. Practical Contributions

From a practitioner's perspective, the research work provides a comprehensive tool to the managerial personnel to improve the production and environmental performance of their organization using contemporary approaches. The framework starts with the conceptualization of lean manufacturing that calls for top management commitment and building a lean team to impart lean knowledge; this phase is equally beneficial to organizations that are aiming to start their lean journey. After the conceptualization phase, lean preparing phase occurs where major problems are identified through Gemba walk and the product family is identified which gives the maximum revenue. Going further, the lean preparation phase exhorts to identify the wastes in the production system whilst identifying the areas where Industry 4.0 technologies can be utilized. The framework uses the approach of validity check via simulation, which forms a basic tenet of process improvement. Following the lean preparation phase, the lean implementation phase commences where the transformation as per future state map ensues. In this transformation, the relevant Industry 4.0 technologies are applied as lean acts as a precursor to Industry 4.0 adoption. After successful implementation on one product family, it can be spread to other product families. On the environmental front, the steps and phases of green manufacturing help the managers in adopting practices that positively influence environmentally benign manufacturing such as ISO 14001 implementation, 6R, use of renewable energy resources, smart energy monitoring etc. However, it must be kept in mind that the lean-green-Industry 4.0 implementation is a gradual process and requires perseverance from top management as well as cultural change in the organization to sustain its benefits.

5.3. Limitations & Future Prospects

Despite the favourable results and holistic nature of the framework, there exist a few limitations in this research work. The framework has only been applied to a medium-scale auto-parts manufacturing firm through a simulation based longitudinal case study and needs cross sectional validation. The concepts of lean manufacturing & Industry 4.0 technologies mentioned in this research work hold true for a medium scale manufacturing firm that is starting its lean and green journey, but organizations with increased maturity levels will require a modified framework tailored as per their requirements. Moreover, the application of this framework in food or chemical processing industries may not yield the same levels of improvement, and the framework would require strategic changes. Furthermore, the results may differ when the framework is applied to large scale or small-scale manufacturing enterprises, as the approach of Industry 4.0 is dependent upon the technology readiness levels of the organization. Regarding the economic aspect, the Industry 4.0 based approach requires a high capital investment; therefore, the small-scale industries will have to make a strategic decision by keeping in view the rate of return on the investment. In addition to that, only GHG emissions of CO_2, CH_4 and N_2O were studied for the manufacturing process; the transportation related emissions were not a part of the calculations. Moreover, the negative social impact of Industry 4.0 technologies has not been discussed in this research work.

The synergy between Industry 4.0 and various manufacturing approaches has been a topic of interest lately, and this research work will help eliciting a useful relationship between them. Furthermore, it will pave way for determining various trade-offs between the manufacturing approaches, to achieve optimized results. Mathematical modelling approaches can be used to study the relationships between the various facets of lean manufacturing, green manufacturing and Industry 4.0. In addition to this, the holistic combination of sustainable manufacturing pillars with Industry 4.0 technologies can produce interesting results in future.

6. Conclusion

An integrated framework that combines lean manufacturing, green manufacturing and Industry 4.0 has been developed in this research work; and favourable results have been achieved upon its implementation in an auto-parts manufacturing firm. For academicians, the research work offers a novel approach to combine the concepts of lean manufacturing, green manufacturing and Industry 4.0 technologies; whereas practitioners can benefit from the positive economic and environmental performance of the developed framework. The GHG emissions from manufacturing were reduced by 54.16%, whereas the lead time, value added time and non-value-added time were reduced by 25.60%, 24.68% and 55.62% respectively. It was observed that the Industry 4.0 technologies of smart production control, cyberphysical systems, automation and smart energy monitoring, complement the improvement in production and ecological performances of a manufacturing process. The framework is divided into six phases and twenty-seven easy steps; and will be extremely beneficial to practitioners in improving the economic and environmental performance of their manufacturing facility. In future, the research work can provide a concrete foundation in discussing the sustainable manufacturing facet with Industry 4.0 for optimized social, economic and environmental performance. While discussing the sustainability and Industry 4.0 synergy, various mathematical modeling tools can be utilized to explicate the trade-offs between the dimensions of sustainability and Industry 4.0. Further research can be carried out using the techniques of sustainable value stream mapping and ergonomic value stream mapping for process visualization. In addition to that, the research work can be expanded to supply chain domain and the Industry 4.0 approach of BigData and IoT can be harnessed for optimized supply chain performance.

Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Supplementary materials

Supplementary material associated with this article can be found, in the online version, at doi:10.1016/j.spc.2021.01.001.

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