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A Lean Manufacturing Approach for Optimization of Lithium-Ion Battery Supply Chains Management

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Abstract

The rise of electric vehicles (EVs), energized by the rapid uptake from customers, is propelling an explosion in demand for -running efficient and economical lithium-ion battery supply chains. In answering the call, this paper delves into the application of lean manufacturing principles to optimize lithium-ion battery (LIB) supply chain management by significantly decreasing waste, lead times, and enhancing overall production efficiency. Lean tools are applied for the analysis of battery supply chain challenges: value stream mapping, just-in-time (JIT) inventory, and continuous improvement (Kaizen), etc. The researchers outlined a solution suggesting that battery cells and modules were having to be made using unnecessarily complex manufacturing processes if the industry wanted at high-quality without buckling under the pressure of burgeoning EV sales. By deploying lean techniques, this research offers practical suggestions to improve flexibility, sustainability and cost efficiency of lithium-ion battery supply chains for wider adoption of electric vehicles. The results are based on commercial mixed iron amorphous metal production applications and represent substantial cost and time-to-market advantages for battery manufacturers as well as a more environmentally responsible approach, in line with the industry imperative to deliver sustainable and scalable battery production.

Keywords: Electric vehicles, supply chains, lean manufacturing, lithium-ion batteries, environmental impact

INTRODUCTION

Supply chains, particularly for the electric vehicle (EV) industry depend on lithium-ion battery production, and therefore the most efficient battery plants are directly correlated with car performance as well as cost. Optimizing these supply chains has become increasingly important as the demand for EVs is increasing [1]. This involves its entire supply chain from extracting raw materials (such as lithium, cobalt and nickel) to manufacturing battery cells and assembling modules up to distribution. The throughput volume per stage and the quality requirements should be high, as we want to make each of those hard running stages count [2]. Higher demand of EVs means improved supply chain management is needed in areas such as raw material scarcity, production bottlenecks and cost high. These points relate to lean manufacturing principles that are all about reducing waste and optimizing the pot of process [3]. Lean strategies enable manufacturers to improve operational efficiencies, reduce lead times and minimize costs, which make productivity and scalability of lithium-ion production easier for the growing EV market as shown in Figure 1.

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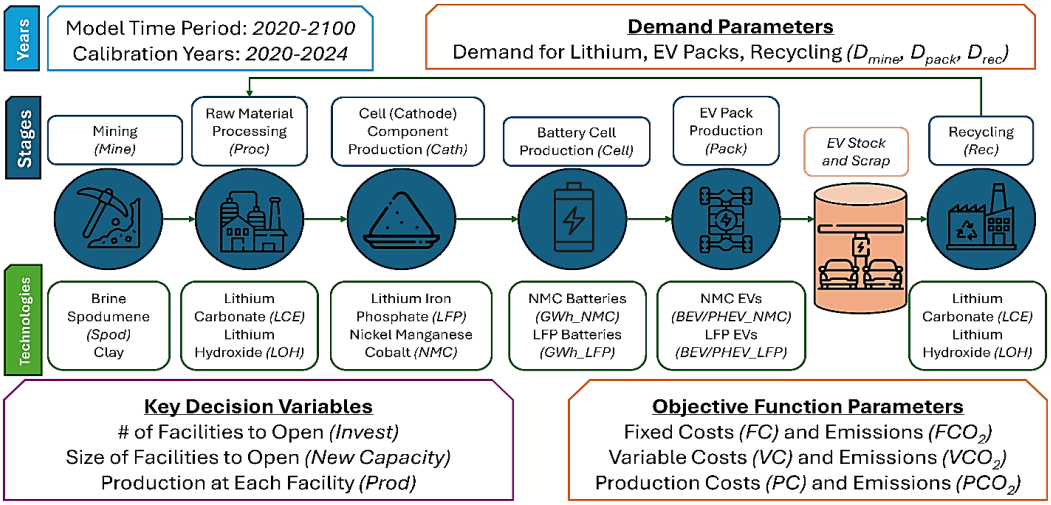

Figure 1. The lithium supply chain and optimization model [1].

Problem Definition

Current lithium-ion battery supply chains are inefficient, costly to produce, filled with excess inventory and have long lead times [4]. These problems result in extra costs, poor timing of operations, variable quality and lack of communication between the parties involved. Two, lean manufacturing eliminates these issues through a focused approach of streamlining processes and eliminating waste to make the supply chain more efficient as a whole leading to increased cost-effectiveness and responsiveness to market demands [5].

Objectives

The goals of implementing lean manufacturing methodology to optimize lithium-ion battery supply chain management are as follows [6]:

1. *Eliminate Waste: Reduce waste*: in the form of inventory, overproduction, or inefficient processes throughout the supply chain you can identify value and no-value added activities to minimize waste and increase efficiency.
2. *Introduction of Efficiency:* By improving on production processes and logistics, you can reduce lead times and cycle lengths, increase throughput, creating a leaner, more responsive supply chain.
3. *Cost Savings:* Streamline Cost Saving process e.g. Inventory optimization, Resource Utilization, readymade Product and Material which in return lower the production costs, Operating cost.
4. *Enhancing Quality:* Standardize the workflows and processes to optimize stable product quality, minimize defects and improve the reliability of lithium-ion batteries.
5. *Inventory Management:* Implement Just-in-Time (JIT) principles to manage your inventory in an efficient way without excessive costs and maintain proper availability of parts when you need them.
6. *Drive constant performance improvement:* Push for continuous process evaluation and refinement, leading to incremental refinements of the ways in which work is done into achieve superior execution.
7. *Strengthening the Supply Chain* – Empowering real-time connections and collaboration between suppliers, manufacturers and distributors to improve visibility, business as will fulfillment, forecasting process refinement with demand.
8. *Scalability:* Create agile and optimized supply chains that can grow as demand for lithium batteries rises with the rise of the electric vehicle market.
9. *Improve Sustainability:* Use lean principles to diminish your environmental footprint (e.g., reduce our demand on resources and improve recycling processes).

Methodology

The Lean manufacturing principles, which is designed to suit lithium-ion battery supply chains by cutting out waste in order to cut back cost and time [7]. Key principles include:

1. *Reduce Waste:* Eliminate non-value added activities throughout the supply chain. This involves cutting down on excess inventory, rectifying defects and ensuring that production does not happen more frequently and faster than needed.
2. *Value Stream Mapping:* Look at the overall supply chain to visualizing each and every step, from raw material sourcing to final assembly and ensure that each stage value add comment will be useful in production flow.
3. *Zero Inventory Planning (JIT):* Install JIT to eliminate waste, which reduces inventory counts by delivering components precisely as needed and reducing holding costs.
4. *Continuous Improvement (Kaizen):* Evaluate and refine processes on a regular basis to promote a culture of ongoing improvement. Welcome feedback and iterate to optimize processing costs gradually.
5. *Standardized Workflows:* Develop standardized workflows to keep everything the same, reduce variability, and help improve your production efficiency. This is one of the ways that we keep our high quality and make our operation more efficient.

Under these lean principles, significant waste reduction is achieved in the lithium-ion battery supply chains as well [8]. This leads to less production costs and time efficiency that supports an increased demand for electric vehicles.

LITERATURE REVIEW

Lean manufacturing is a method of working which aims to add value by minimizing waste through streamlining efficiency [9, 10]. Main principles covered waste reduction, value stream mapping, Just-in-Time (JIT) inventory, continuous improvement /Kaizen and Standard Workflows. They are used extensively in manufacturing environments from high-volume production to even job shops. For various forms of production, such as in the electronics and automotive industries, lean manufacturing has proven to be highly effective [11–15]. Lean principles as applied to lithium-ion batteries can uncover and solve expensive, inefficiencies, or quality related challenges in certain buckets. The lithium-ion battery supply chain has material shortages, production bottlenecks and high costs. Fixing those is an absolute necessity for improving the production of batteries as well as taking care of the increasing electric vehicle (EV) market. The application of lean principles to supply chain management will result in a number of efficiencies and cost savings [16-20]. To overcome this situation techniques like value stream mapping, JIT, Kaizen can be adopted to bring in continuous process improvements and improve overall performance of the supply chain. A few case studies show how lean manufacturing has worked in practice across different industries and sectors, such as battery production [21]. The purpose of these studies is to possess an applied and practical vision associated with the use of lean methods in their implementation and its effect on the performance. Another very necessary step is to partner lean manufacturing with all sustainability initiatives so as to bring down the environmental consequences of battery production. Such practices, derived from lean processes to reduce waste and make resources go further can also render supply chains more sustainable [22-25]. Numerous insights can be derived from lean manufacturing and further elaboration is provided in previous work regarding how best to optimize lithium-ion battery supply chains. Implementing lean principles to solve the pain points of battery production like its high costs and inefficiencies can lead manufacturers a long way in improving the efficiency, cost-effectiveness, and sustainability. Combining lean practices with sustainability work make the battery supply chains more powerful in terms of both efficiency and environmental pay-back. However, the lithium-ion battery supply chain like all value chains is not without its flaws and particular challenges that limit its efficiency. Shortages of raw materials, especially key minerals used in lithium-ion batteries such as lithium, cobalt and nickel are likely to lead to delivery delays and price fluctuations. At the same time, higher production costs, due to complicated

manufacturing processes and large capital investments place more pressure on affordability within the industry [26]. Wait time for everything, from the raw materials to final assembly, give way to delays and latencies. Moreover, the fact that large quantities of raw material and electricity are needed to produce batteries raises environmental issues in terms of waste and pollution, causing the stimulation for more sustainable and green solutions. Lean principles have been applied successfully in many manufacturing sectors, particularly the automotive and electronics industries. The Toyota Production System Lean principles (as applied in manufacturing) blame: In automotive manufacturing, the broad adoption of these principles led to performance breakthroughs, just like those that result from improvements in workflow, stock management and production control. Likewise, lean methodologies are widely used in the electronics industry where companies like Dell and HP have worked with their suppliers to improve inventory management speed up production cycles. Exhibited outcomes prove the utility of lean practices in enhancing operational efficiency, cutting down costs, and elevating market adaptability across a wide range of manufacturing sectors [27]. Even though lean manufacturing principles have been implemented in different industries, there is limited academic focus on the application of lean practices to lithium-ion battery supply chain management. Although these frameworks have worked in fields of automotive and electronics, integrating to lithium-ion battery production where so complex and developing rapidly has been not investigated yet. Unique sectorial challenges including raw material shortages, high production costs and environmental concerns require lean strategies tailor-made for the industry. In doing so, we will provide insights and facilitate the development of methodologies for more efficient battery supply chain while also reducing costs within this strategic area [28].

LEAN MANUFACTURING PRINCIPLES IN BATTERY SUPPLY CHAINS

Overproduction, waiting times, and excess inventory are among the types of waste that can reduce efficiency in battery production and drive up costs as shown in Figure 2. When production quantities are higher than demand, overproduction arises creating dead stock (not the good kind!) and risk of obsolescence for batteries. These waiting times result from all of the delays from one point in production to another, which lead to idle resources and make the production ways last even longer [29]. Holding excess inventory consumes cash and resources, reducing profits through increased holding costs and the risk of obsolescence. In contrast, Lean principles attempt to solve these problems via JIT inventory to tie production directly to true demand; reduction of wait times through smoother processing, and virtually elimination of excess inventory by tweaking production schedules and workflows. These steps also result in increased efficiency, reduced costs, and swift reaction times required for battery production. Value Stream Mapping (VSM) provides a powerful way for studying and streamlining the processes of a lithium-ion battery supply chain right from sourcing these process raw materials to distributing finished batteries. VSM is a method to graphically map each process stage in the supply chain so that inefficiencies, bottlenecks, and non-value-added activities are clear. This enables stakeholders to identify areas delaying the process, leading to over inventories and waste while providing a very systematic approach for continuous improvement. By demonstrating the movement of materials and information, VSM makes it easier to apply lean practices like Just-in-Time production and continuous improvement in the supply chain for improved efficiency, lower costs, and faster delivery times. JIT (Just-In-Time) is a strategy to reduce inventory buffer and enable the delivery of essential components such as cathodes, anodes, and electrolytes for realizing the lithium ion battery production. JIT reduces stock levels and, consequently, holding costs by aligning the production schedule more tightly with actual demand. This could also involve just-in-time deployment of materials, which focuses on precision synchronized timing between suppliers and manufacturers to deliver the components in time for an order. Ensuring that high quality batteries are provided in a cost effective and timely way. JITalso works to enhance the operational efficiency so as to shorten lead times and improve overall supply chain responsiveness. Practices for continuous improvement, often denoted in the philosophy of Kaizen, are also important to ensure that supply chain processes are continuously optimized to improve productivity and resilience. These practices also develop a culture of regular

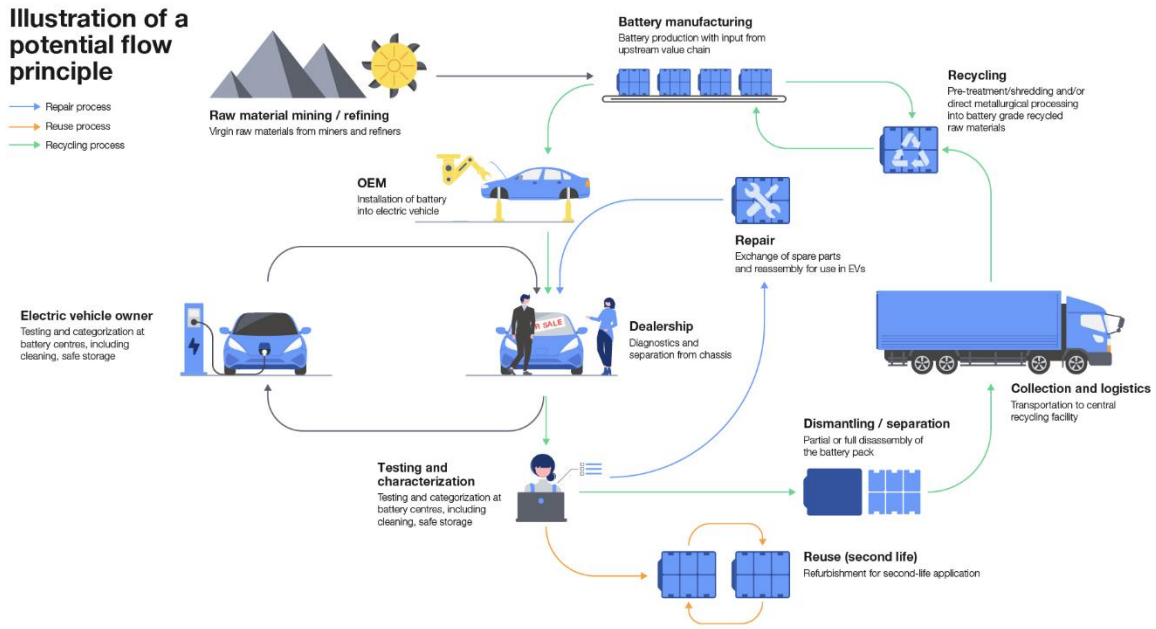

Figure 2. Battery circular value chain
(source: https://www.automotivemanufacturingsolutions.com)

evaluation and step by step improvements to the supply chain operations. They analyze performance data, find ways to improve and implement lots of little things that cumulatively add up to meaningful improvements in efficiency. Such an iterative approach can deliver preparedness for any new challenges as well as flexibility to revise processes over time in order to meet new market conditions and technology innovation cost-effectively. In the battery module manufacturing line, standardized workflows and automation are essential to combat variability and promote consistency [30]. Standard procedures mean that manufacturers have established practices for each step in the production process, and reducing variations from those practices results in improved quality control. Automation takes this a step further by allowing reliable, consistent actions that help minimize human error and also improve production turnaround times. Taken together, these measures will deliver even more consistent and uniform battery modules as well as better return on the overall production efficiency, thereby ensuring each module meets specified standards of performance every time. By reducing procurement timing, cutting costs, and mitigating risks to the supply chain, lean principles can greatly optimize sourcing for critical materials like lithium, cobalt, and nickel. This ensures that materials are sourced exactly when required, saving on excess inventory along with holding costs by following methodologies like Just-in-Time (JIT) and supplier collaboration. Lean principles also favor creation and maintenance of solid supply chain with lean suppliers as well as continual improvement of sourcing strategies. Taking a dedicated approach, we can find issues and red flags in the supply chain before they form long before it becomes a risk to the material flow for batteries an address it as per planned prioritization. Lean Manufacturing Helps Streamline Battery Cell Production: Processes, bottlenecks, waste identified As simple as the concept may sound, implementation is anything but easy; it typically involves identifying and removing wasteful activities (value stream mapping), process stabilization & optimization (continuous flow) and cycle time improvements in manufacturing. Methodologies such as 5S and Kaizen drive efficiencies by creating an organized work environment, standardizing workflows for efficiency, and machining a culture of constant improvement [21]. Lenities make better use of resources, help to reduce lead times and ensure consistent process quality: all tools that improve overall productivity in battery cell production and contribute to cost savings at the operational level. Logistically, lean approaches can directly benefit transportation routes and decrease the amount of time it takes to deliver a product to a customer by emphasizing efficiency and minimizing waste. Value

stream mapping, for example, is one common best practice that companies can use to map out the most efficient path possible while route optimization is another promising solution that allows companies to take proactive control of their own transportation without relying on logistics service providers circuitous routes. Lean practices facilitate real-time data tracking and tighter coordination with suppliers and distribution partners, which in turn helps us to schedule more precisely and to respond faster. Moreover, some methods like cross-docking and synchronized delivery schedules can better optimize the logistics process and reduce overall lead times to ensure timely component and finished product deliveries. The suppliers require to be more co-operative for implementing of lean activities and reducing defects and providing the services on time. Manufacturers that work in close collaboration with suppliers can better coordinate production schedules, quality standards, and inventory levels in advance of receiving raw materials and components to help ensure a smooth flow while reducing potential disruptions. These two attributes the ability to effectively communicate and solve problems together lead to foreseeing these issues before they have a negative effect on production, resulting in fewer defects and more qualitative products. As well as more accurate demand forecasting, better aligned delivery times and tighter supply chain performance for increased productivity and improved manufacturer-supplier relationships.

CASE STUDY

ABC Power Solutions, an eminent manufacturer in the lithium-ion battery sector, encountered a set of supply chain woes like bloated production costs with lackluster material handling and prolonged lead times. To help fight these problems and to make supply management as the whole better, they adopt lean manufacturing way.

Lean Implementation Steps

- *Value Stream Mapping (VSM):* A comprehensive VSM exercise was carried out by ABC Power Solutions for its entire supply chain, from raw material sourcing to battery assembly and distribution. This created a model to map out crucial desiloed areas of wastage and inefficiencies.
- *JIT (Just-in-Time) Inventory Management:* The Company implemented JIT policies to time deliveries of materials with production schedules, in an effort to minimize inventory bloat and its associated carrying costs.
- *Standardized Workflows and Automation:* ABC Power Solutions standardized production workflows and deployed automation in material handling and assembly processes to unify operations and decrease variability.
- *Supplier Collaboration and Integration* – The Company improved material quality and delivery reliability through its closer collaboration with suppliers. HSE rewired itself and arrived at agreed performance measures and joint review meetings.

Value Stream Mapping

Eventually, VSM came into existence with the objective to identify and eradicate waste and redundancy in a supply chain that would complement and enhance its performance as well as responsiveness.

Findings

- The VSM identified that excessive material movement between stages and handling delays were key sources of waste.
- *Raised Lead Times:* Lengthened lead times were witnessed because of raw material and production stage time outs that influenced supply chain performance as a whole.
- *Huge stock positions:* A number of raw material and finished goods maintained in stock resulting in increased carrying costs and obsolesce.

Actions Taken

- *Improved Materials flow:* Re-structured the materials handling processes in order to minimize

motion waste and better connect stages of production.

- *Applied JIT Principles:* By modification of stock position and supplier schedules with regards to materials shipped to fit the need of production would have an effect on any excessive inventories.
- *Strengthened Supplier Synchronization:* More durable and luxurious quality materials to produce because of developed supplier association and communication (well-timed supply).

Success Metrics / KPI (Key Performance Indicators

- *Shortening The Lead Start:* Watched continuously from raw materials in a warehouse until all delivery to complete goods. ABC Power Solutions slashed lead times by 18% after inculcating lean principles that helped to streamline responsiveness.
- *Inventory turnover:* Assessed how often inventory was being replaced. BSC reduced Excess Inventory Levels by 25%, yielding over $1,000,000.00 in annual cost savings.
- *Production Efficiency:* Demonstrated improvements in production yield and cycle times. Standardization of workflows and automation brought 20% production efficiency gain;
- *Quality of produced batteries* Stated as Defect Rates Improved quality control practices led to a 12 percent decrease in defect rates.
- *On Time Material Delivery*: Evaluated the dependability and punctuality of deliveries from suppliers. Collaboration with the integration, collaboration was improved and created 15% on-time delivery measurement ACY Performance Improvement.

ABC Power Solutions has seen significant successes across its supply chain after implementing a lean manufacturing approach. The company could fine-tune the supply chain management by using Value Stream Mapping to detect and fix inefficiencies, applying Just-In-Time inventory, streamlining operations through standardization of workflows, enhancing coordination with suppliers. These are said to have helped slash lead times, cut inventory costs and increase production efficiency so that the business could produce a higher quality product with improved competition in the lithium-ion battery market.

RESULTS AND DISCUSSION

There are multiple challenges when applying lean principles into a lithium-ion battery supply chain. Suppliers often resist such change, they are reminded of having to perform new practices or synchronize closer (jointly invest) with a marketplace partner. Additionally, the cost for smaller manufacturers of implementing lean transformations and investing in automation, training, and process redesign is often much higher than big manufacturers. Audi claims weight reduction is key to its project, but the upper limit for this strategy may well be defined by limited production facilities and difficulties in obtaining materials at scale quickly enough. To address these challenges, an organization must be armed with the right strategy (strategic planning), leadership and a phased methodology to successfully put Lean into practice. On the other hand, if you do not have a stable and secured supply chain due to raw material shortage or geopolitical tension then swift closing is difficult to achieve because of limited supply, global availability has been already compromised. Lean principle would require uninterrupted repetitive cycle with just in time inventory control which can be painful for the manufacturing sector now days because of prolonged order lead times from external suppliers.

- *Lean:* Lean is based on a Just-in-Time (JIT) principles, which means undertaking minimal inventory levels resulting in the risk of production halts due to unexpected supply chain suspensions. Something like a lack of lithium and cobalt can hold up production, drive prices higher and cost you major time as raw materials shortages have the ability to do. These difficulties are then compounded by geopolitical factors such as trade restrictions or tariffs, which can lead to further bottlenecks and uncertainties in the supply chain. These disruptions could prompt manufacturers to hold greater buffer stocks or upon reflection potentially re-visit their lean practices in terms of getting the balance right between efficiency and supply chain management robustness
- Lean manufacturing enables sustainable battery production by minimizing wastage, conserving

resources and optimizing for energy efficiency. What makes these processes work more harmoniously with EV production is due to the principles of lean – when everything comes together all unnecessary activity or waste is eliminated and that naturally leads to a minor scale on material waste and the consumption for raw resources like lithium, cobalt. Practices such as Just-In-Time (JIT) inventory management can reduce the amount of excess inventory, reducing the environmental footprint of wasted materials. Along those same lines, using the most efficient machinery and getting production processes down to a science means lower energy operations during production making it laen best practice. The focus on continuous improvement ensures an environmentally friendly production process, making it also ideal for lithium-ion battery manufacturing that seeks to marry efficiency with larger corporate sustainability goals.

- Incorporating lean manufacturing with the circular economy principles provides a significant opportunity to improve sustainability within lithium-ion battery manufacturing. · Lean is ideal for enhancing the efficiency and productivity at the root of circular economy efforts like battery recycling, material recovery. Including closed-loop processes allows manufacturers to preserve the value of materials such as lithium, cobalt and nickel for longer periods before requiring new virgin inputs. This is where Lean principles come in, helping to streamline these recycling processes by reducing waste and enhancing the availability of recovered materials for production. In addition to the environmental effects mentioned earlier, this integration will both enhance resource utilization and promote cost savings and supply chain resiliency.
- Emerging technologies such as IoT, AI & digital twins could revolutionize the lean manufacturing practices in order to optimize Li-ion battery supply chains. Real-time materials and equipment tracking saves time on inventory management and reacts faster to potential bottlenecks with IoT. AI is able to sift through massive amounts of supply chain data in order to detect inefficiencies and anticipate demand fluctuations that lead for a higher successful operation with less wastage. Digital twins bring the supply chain to life as a virtual representation, allowing manufacturers to plan for and execute process changes by running simulations that optimize the relationship between factories and suppliers. All in all, these technologies support and extend the principles of lean by increasing visibility, speed, and productivity throughout the supply chain.
- *Lean Best Practices:* These principles can be applied to supply chain operations and reduce waste in supply chains, thereby making them more flexible and scalable, allowing them to manage unanticipated shocks or disruptions such as the COVID-19 pandemic or geopolitical activities. Lean supply chains are able to respond with agility to disruptions by minimizing excess inventory (thanks to Just-in-Time [JIT] practices) and optimizing production processes. Moreover, the emphasis on a greater supply chain gain relationship and continuous improvement under lean encourages more cooperation along with innovation that in turn promotes quick source diversification or realignment of operational priorities during crisis times for companies. This adaptability reinforces supply chains, making them sound and capable to withstand external exhaustion.
- Lean manufacturing principles in battery supply chains the opportunity to apply more of these is substantial, as electric vehicle (EV) adoption continues its global momentum. Increased need for lithium-ion batteries will benefit from lean practices that can increase global production capacity with reduced costs by minimizing waste, better resource utilization and more efficient Just-in-Time (JIT) inventory. Lean principles may standardize associated processes, easing coordination through international supply chains and reducing lead times. Additionally, a focus on supplier collaboration and ongoing improvement can lead to innovative outcomes in material sourcing as well as logistics. Scaling lean globally will enable the proliferation, growth and evolution of the EV market.

CONCLUSION

- Lean manufacturing has numerous advantages for supply chains of lithium-ion batteries in terms of cost savings, productivity enhancement and environmental friendliness. Waste elimination, a focus on the speed of production, and Just-in-Time (JIT) inventory management that lean

practices priorities can mean less redundant stock and fewer expenses related to surplus inventory, which can reduce overall production expense. In the context of a marketing agency, Lean also help to improve operational efficiency thus reducing bottlenecks on your workflow and drive up throughput. Lean manufacturing uses resources more effectively, benefiting sustainability through a reduction in waste and energy use. The ongoing process improvement focus also helps to ensure that battery production remains environmentally responsible in line with larger sustainability goals and eliminates any competitive disadvantages as the EV market continues to expand.

- Perform the Value Stream Mapping (VSM): map the entire supply chain processes from mining of raw materials to delivery of batteries. Get to the root of inefficiencies, bottlenecks, and waste areas. Leverage VSM to simplify processes and remove waste.
- Coordinate shipments to arrive with just the right amount of lead time to keep inventory levels controlled resulting in reduced warehouse costs. This limits overstock, and obsolete black box items like lithium, cobalt and nickel are always there when needed.
- You will be working on the delivery of high quality materials on time with suppliers. Create transparent lines of communication, mutual success measurements and develop lasting business relationships allowing for greater reliability and agility.
- Standardize the production processes and laboriously work in optimizing critical schedules for automation enables by increasing repeatability of Battery manufacturing with Operational Efficiency and Lower Defects
- Promote the culture of an improvement by periodically reviewing processes, taking feedback from employees and making small changes to perform more efficiently and waste less and/or adjust to changing demand.
- Integrate IoT for monitoring supply chains in real-time, AI for predictive analytics and digital twins to simulate processes with all the necessary data optimizations before rolling out. These technologies go hand in glove with lean practices and they provide visibility and agility.
- The lean principles can be applied also in logistics, by improving transportation routes, cutting lead times and adopting cross-docking strategies. It is an effective way to save on transport costs and allow faster delivery of materials and products.
- Include lean that promotes some sustainable use of resources for example car organizations could include reducing energy requirements, recycling battery materials or begin implementing closed loop systems. This is both more efficient and better for the environment.
- Long-term outcomes of lean implementation in operational performance, sustainability, and costs for battery production Research into how lean principles affect production scalability as the demand for batteries increases, particularly in ever-growing EV markets, will be very important. In addition, the collaboration of lean with other performance enhancement strategies such as Industry 4.0 technologies, Six Sigma, or even circular economy principles is also new space for research. Research can be to the point of how combined approaches make supply chain more flexible, resilient and high performance; related to technological developments as well as global sustainability challenges.

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