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Enhancing production control in the presence of critical raw materials: the case study of stators for electric engine ⋆

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Abstract: Tools and technologies from the Industry 4.0 paradigm allow automated, reactive, and efficient ways to optimise operations management. However, effective cost reduction and efficiency improvement depend on the tight coordination and design of (i) automated warehouses, (ii) digital twins for production control, and (iii) interconnecting systems for material handling, coupled with simulation and optimisation routines. These interconnections are particularly strategic in sectors involving critical raw materials with price and availability fluctuations, uncertain customer demand, and unreliable assembly machines like the production of electric vehicles. In these cases, inventory management should not be the only driver for operation performance. This paper investigates the effects on inventory management of enhancing production control for a real assembly line of stators for electric car engines. The results show that using priority-based job sequencing increases line WIP but avoids deadlocks, reduces costs, and improves overall efficiency.

Keywords: Job sequencing; Scheduling; Inventory management; Critical raw materials; Discrete-event simulation; Electric car; Stator.

1. INTRODUCTION

Electric cars are essential to reduce the environmental impact of the mobility sector by lowering air pollution (Dlugosch et al., 2022), and their raw materials have a pivotal role. Compared to internal combustion engine cars, electric vehicles have a drastically smaller Bill of Materials, a longer average lifecycle, and require fewer maintenance interventions (Li et al., 2019). Although electric cars contribute to mitigating environmental impact, particularly when charged with renewable energy, their production is more critical and less sustainable than common cars due to the minerals they need (Schreiber et al., 2021).

Minerals exploited for producing engines and battery packs for electric cars are considered critical due to the limited availability and the geopolitical and commercial dynamics that increase price and supply volatility (Jones et al., 2023). The combination of price and supply volatility impacts the average production cost faced by manufacturers importing critical raw materials from other countries, leading to the non-competitively high final cost of their products for electric vehicles (Yang et al., 2022).

Inventory management is critical in all those fields, like electric vehicle manufacturing, involving fast obsolescence rates, perishable raw materials, technology disruptions, and fluctuant and variable customer demand (Plaza et al., 2018). Moreover, the more critical and challenging it is to handle the raw material and subproducts (e.g. size and weight), the more closely linked inventory management and production system optimization are (Eberlein et al., 2021).

The scientific literature focuses on investigating the risk of supply chain disruptions (Althaf and Babbitt, 2021), reduction of dependence on critical raw materials through technological innovation and raw material substitution (Ortego et al., 2020), and rearrangements of the global supply chain (Yang et al., 2022). On the demand side, the research aims to identify schemes for supporting governments and decision-makers in financing a smooth and orderly transition towards electric mobility (Amante García and Canals Casals, 2024). However, few efforts have been directed to address the impacts of production control and the consequent design of the manufacturing system and the management of such complex inventories. Moreover, the uncertain supply and demand conditions worsen the consequences of variability propagation through the entire value chain (Yang et al., 2021). The new industrial paradigm offers a wide set of technologies; however, in such an economically stressed sector, the return on investment should be carefully evaluated to ensure short and long-term competitive advantage and profitability.

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This paper analyses the effects on inventory management performance of enhancing production control in a real and fully automated system to produce electric vehicle engines. In particular, the paper focuses on the assembly line of the stator of the electric vehicle engines as it involves critical resources, is subjected to frequent failures, and consists of a dedicated flow line working jobs according to a FIFO priority. Three Key Performance Indicators (KPIs) are investigated: raw material consumption rate (the system throughput), daily fluctuation in the raw material consumption rate (system throughput standard deviation), and inventory turns that highlight the reduction of the inventory dedicated to the production of the electric engine stator.

In the remainder, Section 2 presents the state of the art, Section 3 defines the addressed problem, and Section 4 presents the preliminary results. Finally, Section 5 concludes the paper.

2. BACKGROUND

Two of the main problems in the assembly line of stators for electric engines are the reliability of the machines and the difficulties in handling parts (that require conveyor systems). Therefore, the assembly line can be modelled as a flow shop with constrained transports and reentrant flows (to manage reworks and iterative processes). Investigating the impact of these systems on inventory management jointly with the production system is difficult. Indeed, a general framework is missed even though this kind of system has been tackled in the literature. As an example, an analytical model has been proposed to investigate the performance of a flow shop line with continuous transport (like a conveyor) (Fan and Su, 2022). On the other hand, discrete event simulation has been exploited to investigate the impacts of such kinds of systems in the intralogistics field. Examples are truck scheduling (Chen et al., 2023) and expected waiting time at the loading station bay to enter into the conveyor loop (Bozer and Hsieh, 2004). Other studies investigated material supply for low volumes industries exploiting unpaced lines (Eberlein et al., 2021), material sourcing problems in the field of sport electric cars (Graham et al., 2019), and performed a technological and economic analysis of logistic activities in automotive anterior parts manufacturing (Kavka et al., 2020).

The raw material consumption predictability depends on the standard deviation of the throughput (TH); higher standard deviations indicate significant frequent and unpredictable fluctuations in raw material consumption, leading to larger inventories to ensure high service levels (Hançerlioğulları et al., 2016). Large inventories and low inventory turns are critical for raw materials with high price volatility and unpredictable availability (Plaza et al., 2018).

However, in the stator assembly line for electric car engines, machine reliability and difficult material handling reduce the opportunity to plan production. Therefore, in the literature, inventory management is the only area deputed to mitigate the negative effects of price and fluctuations in the availability of critical raw materials, variable demand, and assembly line variability. The overall production and cost efficiency are stuck in the middle of the tight interactions among (i) manufacturing processes, (ii) inventory management, and (iii) material handling systems (Horn and Podgorski, 2021).

This paper aims to give directions on how to avoid improving the stand-alone efficiency of one of them while neglecting the others. In fact, this can lead to misleading considerations and actions that fail to tackle the actual causes of inefficiencies.

This paper utilises discrete event simulation to examine whether careful planning of production, in light of the handling systems, can reduce overall costs and enhance efficiency. The two identified KPIs can be influenced by enhancing production control and impacting inventory management. In particular, this paper exploits the material consumption rate that depends on: (i) the presence of deadlocks (DL) and (ii) the line throughput (TH).

3. PROBLEM DESCRIPTION

The system considered in this paper is part of a real assembly line of engines for electric cars. In particular, the system under investigation involves the workstations for the stator assembly. The system is a flow shop in which six workstations (WS) are connected through a closed-loop conveyor belt with some carousels (namely, loops) that allow the recirculation of jobs waiting to be worked by the workstations.

Fig. 1 shows the six workstations from WS1 to WS6 and the conveyor loops that allow job recirculation, creating a buffer for busy machines. The system follows a push logic. Specifically, the jobs enter the system with a fixed interarrival rate, and the loading and unloading bays (in orange in Fig. 1) for the job entering and leaving the system are located before WS1 and after the workstation in charge of quality control (WS-QC), respectively.

All WSs are single machines except for WS2 and WS5, which have two parallel and identical machines. The stator production cycle involves a fixed number of layer crimping and layer welding operations for the stator hairpins, causing re-entrant flows for WS5 handled by the conveyor loop involving WS4 and WS5 (N cycles shown in red arrows in Fig. 1).

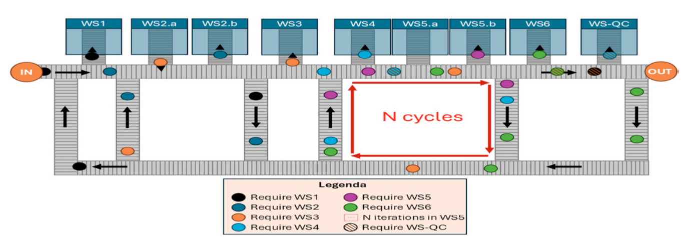


Fig. 1. Assembly line for the stators of electric engines. The assembly line comprises six workstations and a workstation for random quality control (WS-QC). In each conveyor intersection, a gate system directs the jobs towards the shortest path for the WS they are waiting for. Orange circles indicate the load and unload bays for jobs entering or leaving the system.

The machines are unreliable, randomly producing defective jobs; therefore, the workstations are equipped to detect the potential presence of defects in the just worked job, sending it to the last workstation of the conveyor (i.e. WS-QC) that performs quality control. WS-QC checks the actual presence of defects in the jobs and, in that case, tries to restore them. Restored jobs are sent back to the station of origin to be reworked. Instead, jobs without defects are sent to the workstation after the one that has requested the quality check. Jobs with critical defects are discharged out of the system.

3.1 Implementing production control

The experiment analyses the effects on inventory management of implementing production control. The system presented in Fig. 1 allows no production control as the jobs entering the system are identical and move through the conveyor loops until the workstation needed for the successive operation is idle.

To implement the production control with a minimum layout change, the addition of a new conveyor loop for quality control is evaluated. Fig. 2 shows the stator assembly system extended with the carousel for WS-QC, allowing the change of the sequence of jobs requiring quality control. Job sequencing enables several strategies for prioritising jobs and can be extended with real-time system control. It represents the minimum level of change in the system to assess the inventory management cost reduction through production optimisation. Another strategy is the control of the conveyor intersection system gate (namely the points where two or more conveyors diverge or converge, respectively, in pink and yellow in Fig. 2). However, the effectiveness of controlling conveyor split and merge points strictly depends on the lengths of the conveyor loops. Hence, the sequencing option has been chosen to provide general insights into the benefits of production control for inventory management.

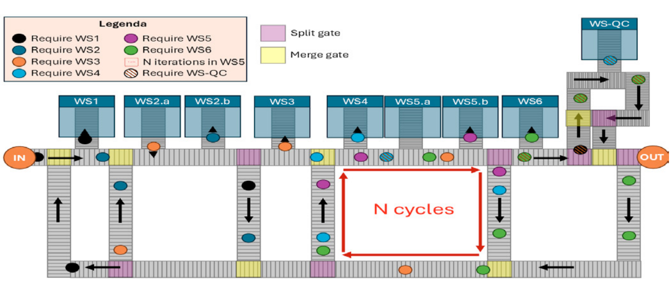


Fig. 2. Assembly line for the stators of electric engines extended with a conveyor loop for production control in WS-QC.

Two KPIs have been considered to assess the impact of real-time control of the stator assembly line on inventory management: (i) the consumption rate of raw materials and (ii) the consumption predictability. The consumption rate (or flow rate) is crucial for increasing inventory turns. According to Little's Law (Eq. 1), and knowing that inventory turns are the inverse of the flow time (Eq. 2), the inventory turns increase with the flow rate and decrease with WIP level (average inventory) (Terwiesch and Cachon, 2024).

$$WIP = flow\,time * flow\,rate. \tag{1}$$

$$inventory\,turns = \frac{1}{flow\,time} = \frac{flow\,rate}{WIP}. \tag{2}$$

The flow rate of raw materials depends on two elements of the stator assembly line: (i) the presence of deadlocks (DL) and (ii) the line TH (i.e. the number of finished jobs per time unit). In automated manufacturing systems, the DLs are system states characterised by paralysis; the system cannot move from the current DL state to another without an external action that forcedly changes the system state (Du and Hu, 2020). Fig. 3 shows an example of DL in the system under investigation, in which the conveyor loop involving WS4 and WS5 is full of recirculating jobs, WS4 cannot unload the processed jobs, and no other jobs can enter the loop, determining a stagnation of the assembly line. DLs in this system can be very disruptive as they require stopping new job arrivals and manually handling job processing into the workstations, causing delays and congestion.

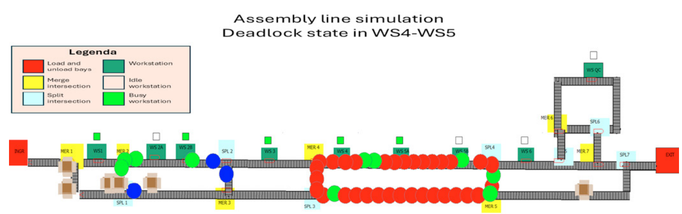


Fig. 3. Simulation on Arena of a deadlock state in the assembly line at the conveyor loop involving WS4 and WS5 preventing WS4 from releasing the processed job and remaining in busy machine state (green box over WS4).

A way to prevent DLs is to monitor system states. When a state with a high risk of leading to DLs is reached, the job inter-arrival time r_a is temporarily increased until normal condition states are reached. However, this strategy also impacts the TH, which is tightly linked to the job arrival in the system. In particular, the TH is the inverse of the job inter-arrival time into the system r_a (3). Therefore, unless the inter-arrival time increases, only job discard due to critical defects can reduce the TH.

$$TH = \frac{1}{r_a}. \tag{3}$$

The predictability of raw material consumption depends on the standard deviation of the TH. The TH standard deviation is influenced by the variability caused by the job inter-arrival times into the system, the processing time variance of the workstations, the random actions of defect repairing (causing job reworks), and the false positives sent to the quality check (i.e. jobs that must do a quality check even if they do not have defects).

3.2 Job sequencing rules

The job sequencing rules are designed by considering the most significant variables impacting TH and its standard deviation: (i) the WS that sent the jobs to the WS-QC for quality check, and (ii) the current presence of other jobs waiting for WS i, namely, the work-in-process of station i (WIP_i).

Performing a quality check on a job coming from the first WSs (e.g. WS1 and WS2) before a job coming from the last one (i.e. WS6) can increase the WIP on the assembly line due to the transportation through conveyors. Conversely, it may increase the WIP without increasing the TH, which will cause lower inventory turns (see Eq. (2)).

Moreover, this paper investigated whether job sequencing may reduce the risk of DLs and allow higher TH by reducing the pressure on the most critical WSs. Consequently, the highest priority is assigned to WS with the lowest WIP, while jobs from WSs with large WIP wait to be worked into the WS-QC conveyor loop rather than increasing the pressure close to the WSs.

The WIP_i and the source station i have been combined to develop mixed strategies. Equations (4) and (5) represent two strategies for determining the priority $p_{j,i}$ of a job j coming from WS i considering (i) the WIP_i of the sending WS i, and (ii) the larger priority given to the first WSs or last WSs, respectively. The parameter α defines the importance given to the first term of the formula (i.e. highest priority to jobs requiring WSs with lowest WIP) or the second one (i.e. highest priority to jobs requiring WSs close to the line load or unload bays, the first or the last ones, respectively).

$$p_{j,i} = \alpha * \frac{\sum_{i=1}^{6} WIP_i}{WIP_i} + (1-\alpha) * \frac{i}{6}. \tag{4}$$

$$p_{j,i} = \alpha * \frac{\sum_{i=1}^{6} WIP_i}{WIP_i} + (1-\alpha) * \frac{1}{i}. \tag{5}$$

Equation (4) prioritises jobs requiring WSs closer to the end of the line, and this strategy will be named *incremental*. Conversely, Equation (5) gives priority to jobs requiring the first WSs and will be named *decremental* as the priority decreases with the increase of the WS number.

These two strategies have been combined to define six job sequencing rules to assess the possible impacts of production control on inventory management:

- *FIFO*. First-in, First-out strategy obtained with no job sequencing. It represents the benchmark;
- *Balanced incremental*. Parameter $\alpha = 0.5$ to give the same importance to WIP and *incremental* strategies;
- *Balanced decremental*. Parameter $\alpha = 0.5$ to give the same importance to WIP and *decremental* strategies;
- *Incremental*. Parameter $\alpha = 0$ to apply only the *incremental* strategy;
- *Decremental*. Parameter $\alpha = 0$ to apply only the *decremental* strategy;
- *WIP*. Parameter $\alpha = 1$ to apply only the *WIP* strategy.

3.3 Design of Experiment

The experiment aims to investigate whether implementing production control through job sequencing at the WS-QC can impact TH and TH predictability, which in this industrial field are also considered relevant for cost reduction in inventory management. For this reason, the system has been approximated to highlight the potential impact of production control on the two KPIs. In the real system, the effects might be more significant, but because of the wider variability propagation, the cause-effect relationship would be difficult to investigate.

The approximated system considers only one operation per job in WS5 rather than the required N cycles. At the same time, WS-QC detects only repairable defects, repairs the jobs, and sends them back to the original workstation for rework. In fact, discarding jobs with critical defects would have biased both TH and TH standard deviation, while detecting false positive requests for quality checks would have biased TH standard deviation.

Workstation processing times and new job inter-arrival times in the system are considered deterministic to isolate and highlight the TH standard deviation managed through job sequencing. It is a reasonable approximation as automated processes generally have small standard deviations (Inman, 1999) and, in this system, the inter-arrival times are usually controlled to prevent DLs.

The approximated line is balanced: each workstation has the same processing time, while parallel machines have twice the processing time to ensure the same overall processing time. The probability of introducing defects is 0.15 in each workstation.

Table 1 presents the parameters and factors of the experiment on the top and the bottom of the table, respectively. In particular, the factors are (i) the job sequencing rule and (ii) the inter-arrival time. Parameters are the factors with only one level, such as processing times and defect probability.

Table 1. Experimental parameters and factors.

Parameters

Parameter	Levels	Parameter	Levels
Processing time WS1	20 min	Processing time WS-QC	20 min
Processing time WS2	40 min	Defective probability	0.15
Processing time WS3	20 min	Processing time WS5	40 min
Processing time WS4	20 min	Processing time WS6	20 min

Factors

Factor	Levels	Factor	Levels
Job sequencing rule	FIFO, Inc. Dec., Bal. Inc., Bal. Dec., WIP	Inter-arrival times	30 min, 32.5 min, 35 min

The discrete event simulation model of the approximated system is used to perform a one-year simulation preceded by one year of warm-up to overcome the transitory period. Arena Rockwell software has been used to perform the simulations.

Each scenario has been simulated one hundred times. The full factorial experimental plan (18 scenarios) has been simulated, and the KPIs measured in each scenario are compared through scenario analysis.

4. RESULTS

The scenario analysis highlights the benefits of implementing production control by job sequencing at the WS-QC by adding a conveyor loop. Fixing an inter-arrival time value with a low probability of leading to DLs prevents inventory management from significant disruptions. However, reducing inter-arrival time reduces DL probability but decreases inventory turns.

Fig. 4 shows that *Incremental* job sequencing rule reduces DL probability for all the three inter-arrival time levels. The probability of DLs has been assessed by counting the DLs that occurred in one hundred replications of the simulation of the same scenario. In particular, it performs better than *FIFO* rule, which is the benchmark. Also, *Incremental* rule allows to set the inter-arrival time to a lower level, maintaining low the DL probability (i.e. larger TH without the negative effect of more probable DLs).

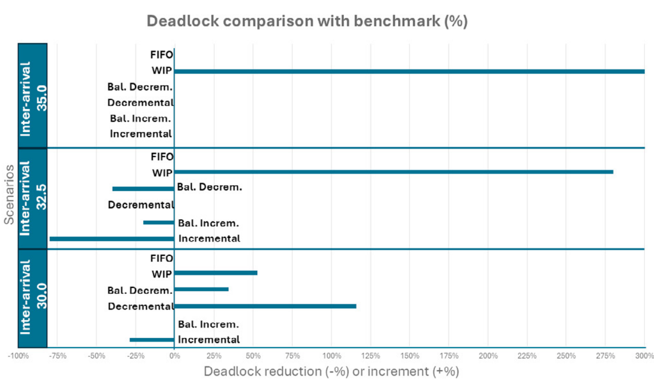


Fig. 4. Percentage of deadlock reduction or increase with respect to the benchmark scenario under the three inter-arrival time levels.

Fig. 5 highlights the impact on daily TH predictability. In fact, average TH is fixed and determined by inter-arrival time level r_a. Still, the system variability leads to fluctuations in the daily TH that impact raw material consumption and inventory management. Production control impacts TH predictability, highlighting that in the case of a balanced line, the *Incremental* strategy performs like the benchmark. However, it is important to implement production control as in real systems, which are characterised by worse balancing and higher system variability, job sequencing can help to improve TH predictability as it influences TH standard deviation.

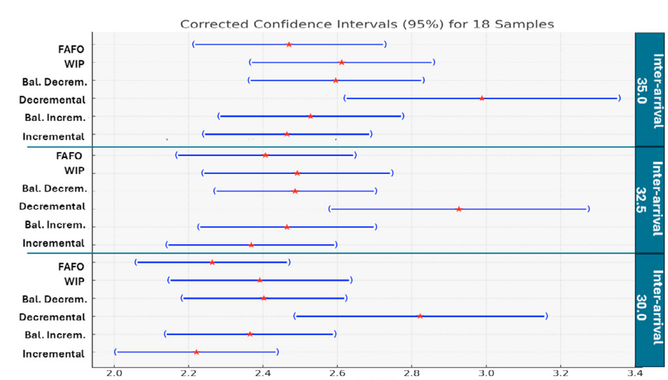
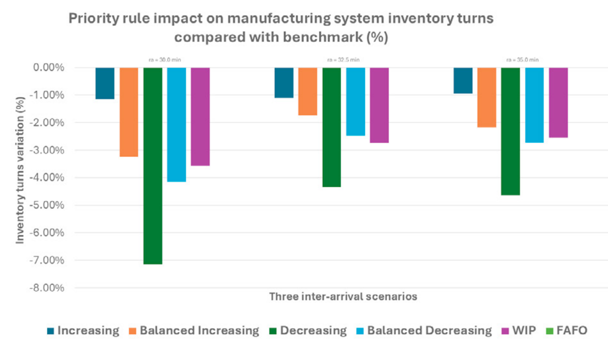
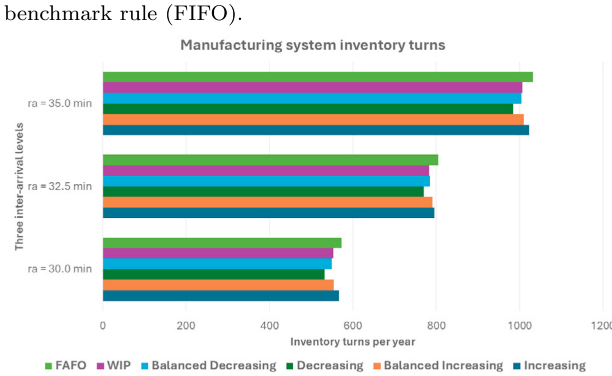


Fig. 5. Confidence intervals for the standard deviation of the daily inter-departure times for the six rules under the three inter-arrival time levels.

The inventory turns, observed by the inventory management point of view, increase by 6.9% as they are proportional to the TH (see Eq. (2)) and *Incremental* priority rule allows to DL-safely increase the TH from 0.028 job/min ($r_a = 35\ min$) to 0.031 job/min ($r_a = 32.5\ min$). From the manufacturing system point of view, Figures 6a and 6b show the impact on manufacturing system inventory turns of the priority rules in the three inter-arrival scenarios. In particular, Fig. 6a shows that in the case of a completely balanced assembly line, the proposed priority rules reduce the inventory turns per year compared with the benchmark rule FIFO, and *Incremental* priority rule (blue column in Fig. 6a) is the best one since leads to the lowest inventory turns reduction. Also, *Incremental* priority rule allows to set an inter-arrival rate of 32.5 minutes safely (i.e. preventing deadlocks). However, this TH increase leads to higher line congestion (i.e. higher WIP) that reduces the manufacturing system inventory turns from around 1000 per year to around 800 per year (Fig. 6b).



(a) Individual performance of priority rules compared with the benchmark rule (FIFO).



(b) Inventory turns per year for the three inter-arrival levels.

Fig. 6. Inventory turns under the three inter-arrival levels and six priority rules.

5. CONCLUSION

The experimental results highlight the importance of evaluating cost reduction strategies by simultaneously considering the interactions between systems for material handling, manufacturing systems, and inventory management. In particular, this approach is important for sectors characterised by high production costs determined by the use of critical raw materials in terms of availability and price volatility, fluctuating demand, and high technological obsolescence rate.

The importance of production control has been investigated through a case study developed by approximating a real assembly line for stators of electric engines for electric cars. The real system is characterised by high automation and transport through workstations by conveyor carousels. The introduction of a new conveyor loop for enhancing job sequencing at the WS for quality control allowed the assessment of the role of scheduling in increasing inventory turns by raising the TH, avoiding disruptive deadlocks, and reducing TH variability.

The proposed approach and the obtained results relate to a sector with high raw material costs and price volatility, and they cannot be generalised to all industrial contexts and systems. Furthermore, a 15% probability of introducing defects may be impractical in certain industrial systems; thus, future research ought to determine how the proposed approach behaves when this probability varies.

However, the results achieved in this paper pave the way for future research in production control to support inventory management through more sophisticated approaches. These include dynamic job management in the conveyor loops by controlling the intersection gates, the development of a real-time control system for a digital twin of the system, and more sophisticated rules for job sequencing. Furthermore, a bird-eye overview considering the entire production of electric engines can extend this approach to assess the overall achievable cost reduction.

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