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Bottleneck Identification and Capacity Improvement of the Tube Processing Section in RAC Manufacturing: A VSM–SMED–Capacity Modeling Approach

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Abstract

This research paper examines production bottlenecks in a Room Air Conditioner (RAC) manufacturing line to establish the operation that restricts monthly production. The system level capacity analysis of the entire station showed that the Tube Processing Section which was in charge of expansion and reduction of the copper tubes was the bottleneck, whereas other stations had enough capacity. This section was analyzed in detail in terms of time study, Value Stream Mapping (VSM), SMED principles and capacity modelling. As of now, it is observed that the section needs 873.48 machine-hours per month whereas there is 572 hours which is insufficient leading to 301.48 hours deficit in machine capacity. Three scenarios of improvements were considered. Option A (SMED and optimization of operator) is a reduction in the amount of non-value-added time but is still inadequate with a need of 768.66 hours. Alternative bargain (a high throughput replacement machine) fulfills requirement when there should be at least 32 percent decrease in processing time and no die-change losses. The most robust proposal is option C (two parallel machines) which has 454.21 hours necessary. The feasibility analysis shows that structural capacity expansion to eliminate the bottleneck must be done by using either option B or C. The analysis offers a decision model that is tested and valid to improve the capacity and justify the investment decision that the company wants to make in new tube-processing devices.

Keywords
Bottleneck Analysis; VSM; SMED; Capacity Modeling; Feasibility; Tube Processing; RAC Manufacturing.

1. Introduction
1.1 General
The manufacturing industries are under pressure to become more productive and ensure constant delivery performance as the customer demand increases. In the production of Room Air Conditioners (RAC), there are several sequential operations which are connected, and the slowest or overloaded station of the line ultimately determines the throughput of the line. Hence, the strategies to prevent the problems with the capacity stability and the ability to meet the monthly output requirements include the identification and improvement of the bottlenecks. The management of the RAC manufacturing line studied noticed that there were some shortcomings of monthly production periodically and therefore an investigation was conducted to establish the cause of the shortage. An

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evaluation at system level of the entire stations indicated that the only section that could not handle the required capacity was the Tube Processing Section that does diameter expansion of copper tubes and reduction of the diameter. Other stations had enough throughput, and therefore, Tube Processing Section was proven as the bottleneck of the whole line.

This part of the operation is a multi-product, batching operation, in which case the tubes are being expanded or reduced, which is on the same machine by a single operator, who alternates between operations as well as periodically changing the die. The features lead to long cycle time, immense setup waste, operator time delays and downtime of the machine. This implies that the process time of the section will be much higher than the machine hours present which will directly constrain RAC output.

In order to solve this problem, the research used the combination of Value Stream Mapping (VSM) to determine the current-state working process and waste and SMED principles to find the possibility of minimizing the changeover and capacity modeling to measure the necessary number of machine-hours in different scenarios of improvement. They tested 3 options of the future state, namely: (A) improvement of the process via SMED and optimization of the operators, (B) substitution of the machine with a more throughput machine and (C) add an extra machine that would be running concurrently. To find out which scenario will potentially work to remove the bottleneck and meet monthly demand, a feasibility analysis was performed.
The paper will include the full diagnosis of Tube Processing Section, assess the effectiveness of the suggested strategies of improvement, and the approved decision-making framework effectual to the selection of the most efficient capacity improvement alternatives to RAC manufacturing.

1.2 Objectives

The objectives of this study are:

1. To identify and quantify the Tube Processing Section as the bottleneck in the RAC manufacturing line using time study, VSM, SMED, and capacity modeling techniques.
2. To evaluate improvement options and determine the most feasible solution to eliminate the bottleneck and meet monthly demand.

2. Literature Review

Lean manufacturing focuses on the systematic removal of any waste material and constant improvement to help optimize productivity and efficiency of the workflow. Value Stream Mapping (VSM) has turned out to be among the most commonly utilized lean tools in order to visualize the material and information flow, determine what non-value-added activity is present, and create a better future state process. The article offered in Lean Manufacturing Implementation Using Value Stream Mapping at an Excavator Manufacturing Company shows that VSM is suitable in diagnostic work of multi-stage, complex production processes and identify bottlenecks due to long setup times, unbalanced workloads, and inefficient material handling (P.M. Masuti, 2019). This has a direct bearing on the current research wherein the Tube Processing Section has comparable flow restrictions as a result of mixed-products and high frequency of die changes.

VSM's applicability extends beyond traditional manufacturing, as seen in *Value Stream Mapping for Smart Pharmaceutical Management in a Thai Hospital*, where VSM was used to streamline pharmaceutical logistics and improve operational visibility (Ganda Boonsothonsatit et al., 2025). This study shows that VSM is capable of integrating material and information flows, an important capability for environments such as tube processing, where operator scheduling, die-change information, and batch sequencing play critical roles in determining capacity (J.M. Rohani & S.M. Zahraee, 2015).

Single-Minute Exchange of Die (SMED) has been broadly used to supplement VSM in order to decrease setup and changeover times. The original SMED methodology by Shingo offers an organized strategy on how to transform internal setup operations into external and streamline the rest of the internal operations(M. Maalouf et al., 2015). Various empirical studies e.g. those in food-processing, printing, and metalworking processes, record set-up time savings of 40-70 percent with the outcome being better equipment accessibility and less downtime (M. Delić et al., 2019).

The studies combining VSM and SMED have shown that both are complemented in their ability to diagnose and remove process waste. Surveys in SMEs and industries indicate that VSM gives us a system perspective of process flow and SMED considers the particular contributors of bottlenecks to changeovers and operator delays. As an illustration, a combination of VSM and Kaizen in flexographic printing resulted in a drastic increase in productivity and a decreased non-value-added time (P. Kaushik & D. Khanduja, 2019). Likewise, more recent

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uses of VSM in metal-part fabrication have demonstrated these reductions of lead-time and better process efficiency by redesign of the future workflow (A. Pereira et al., 2024).

This synthesized approach plays a gap in the current body of knowledge where the capacity feasibility analysis is not usually closely linked with the implementation of VSM-SMED. Overall, the reviewed literature establishes three key insights that frame the methodology of this study:

1. VSM is an effective diagnostic tool for visualizing process flow and identifying production bottlenecks;
2. SMED is a proven approach for reducing setup losses in mixed-model manufacturing; and
3. capacity modeling is essential for determining whether lean improvements alone can satisfy production requirements.

By integrating these methods into a unified analytical framework, this study advances the understanding of bottleneck-focused capacity improvement in RAC manufacturing.

3. Methodology

3.1 Problem Definition

The monthly production output of the Room Air Conditioners (RACs) manufacturing line was consistently falling short. To determine the underlying cause of the capacity limitation and assess workable improvement strategies, management needed a structured industrial engineering study. According to preliminary discussions, delays may be caused by specific operations related to the preparation of copper tubes, particularly the expansion and reduction processes. But it was unclear how much of an impact they would have. Thus, the central issue of this research was identified as:

Determine which station limits the line's overall capacity, measure the difference between processing time needed and available, and create workable improvement plans that can satisfy monthly RAC demand.
Using engineering tools like time study, VSM, SMED, and capacity modeling, the study aims to identify the system bottleneck and assess potential solutions.

3.2 Selection of the Critical Section

To determine the operation limiting monthly output, a thorough evaluation of the Room Air Conditioner (RAC) production line was carried out. Each of the main stations—fin press, coil production, assembly, testing, and tube processing—was assessed using: Fin press, coil production, assembly, testing, and tube processing were all assessed using the following methods:

- Cycle time assessment
- Shift and working-hour analysis
- Monthly demand comparison
- Machine availability and operator allocation
- Required vs. available capacity calculation
-

Monthly demand and observed cycle time were used to calculate the necessary machine-hours for each station (Figure 1). These figures were contrasted with the plant's monthly machine-hour availability of 572 (26 days × 2 shifts × 11 hours). All stations, with the exception of the Tube Processing Section, had adequate capacity, according to this line-level analysis, making Tube Processing the crucial section limiting RAC output.

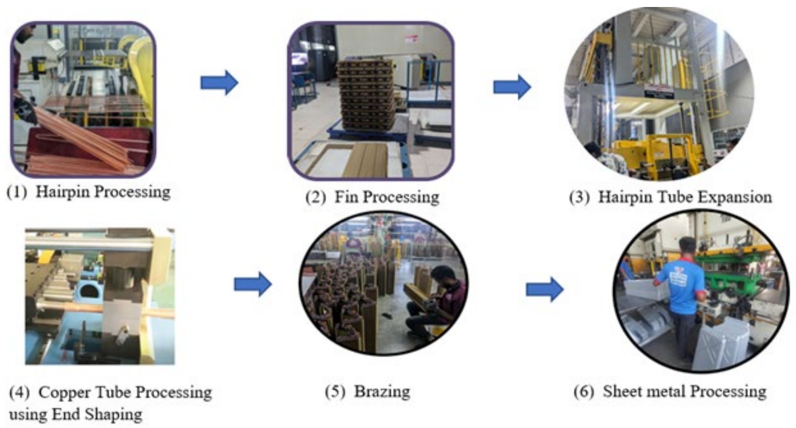

Figure 1: Core Parts Processing Line

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Five of the six stations operated within available capacity, with sufficient buffers to meet monthly production targets, according to the line-level capacity analysis. But there was a big gap at Station 4, the Tube Processing Section, where the necessary processing hours were much more than the available capacity. According to this research, the Tube Processing Section is a crucial bottleneck in the RAC production process. Station 4 directly limits total RAC production because the overall line throughput cannot surpass the output capacity of its slowest station. The study shows that the Tube Processing Section is the only thing that limits production output by mapping all six stations and comparing their performance in numbers. This makes it the main area for improvement and capacity building efforts.

3.3 Current State Analysis

The current state analysis finds major problems in the tube processing section, mostly because of the End-shaping machine's limitations and the fact that the dies have to be changed often. To meet monthly AC production needs and improve overall production efficiency, these problems must be fixed.

Key Parameters:

- Working Days in a Month: 26 days
- Operators for the End-shaping Machine: 2 operators (1 per shift)
- Shifts per Day: 2 shifts
- Working Hours per Shift: 12 hours
- Breaks per Shift: 1 hour (lunch/tea)
- Actual Working Hours per Shift: 11 hours
- Available Working Time in 1 Month: Operating Days× Shifts per Day× Shift Duration 26×11×2=572 hours

This calculation shows that the total available working time for the End-shaping machine in one month is 572 hours.

Monthly AC Demands:

- 1 Ton : 6,000 units
- 1.5 Ton : 12,000 units
- 2 Ton : 2,000 units

Total Units: 20,000 units

The following Table 1 presents the tube requirements for different RAC tonnage categories, including the number of expanded and reduced diameter tubes needed per unit and their corresponding total monthly quantities. These calculated tube demands serve as essential input data for analyzing the workload of the tube processing section and evaluating its capacity, bottleneck behavior, and improvement opportunities.

Table 1. Monthly Tube Demand for Different AC Tonnage Categories

Tonnage	Expanded Diameter Tube per unit AC	Total Expanded Diameter Tube	Reduced Diameter Tube Per unit AC	Total Reduced Diameter Tube
1 Ton	10 units	(6,000×10)= 60,000 units	2 units	(6,000×2)=12,000 units
1.5 Ton	6 units	(12,000×6)= 72,000 units	2 units	(12,000×2)= 24,000 units
2 Ton	11 units	(2,000×11)= 22,000 units	0	0

Table 1 shows the total expanded diameter tubes required to fulfill one month's demand are 154,000 units (60,000 + 72,000 + 22,000). The total reduced diameter tubes required to fulfill one month's demand are 36,000 units (12,000 + 24,000).

3.4 Time Study

A stopwatch time study was performed to obtain accurate cycle times and setup losses. Multiple observations were collected to reduce variability.

Tube Expansion (1 Step):

- Time for 10 pieces: 130.1 seconds
- Time per unit: 13.01 seconds

Tube Diameter Reduction (3 Steps):

- Time for 10 pieces: 282 seconds

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- Time per unit: 28.2 seconds

Die Change:

- Die changes occur 12 times in 1 shift (as reported by the operator).
- Time for each die change: 3.36 minutes = 201.6 seconds

3.5 Capacity Modeling

The precise difference between processing requirements and available hours was measured through capacity modelling. The total processing time needed for die change, tube reduction, and tube expansion is summarised in Table 2. In order to assess the overall workload of the tube processing section and ascertain whether the current capacity is adequate to meet production demand, the computed time values—expressed in seconds and converted into total hours—are used as input data.

Table 2. Total Working Hours Required to Fulfill the Target.

Tube Expansion	154,000×13.01=20,03540 sec
Tube Reduction	36,000×28.2=10,15200 sec
Die change	210.6×26×12×2=1,25898.4 sec
Total time	873.48 hours

3.5.1 Processing Hours Calculation

$$\text{Processing Hours} = \frac{\text{Volume} \times \text{Cycle Time}}{3600}$$

Using monthly demands:

- Expansion: 154,000 units
- Reduction: 36,000 units
-

Processing hours = 838.54 hours/month

3.5.2 Total Required Hours

$$\text{Total Required} = 838.54\text{ h (processing)} + 34.94\text{ h (die changes)} = 873.48\text{ h}$$

3.5.3 Capacity Gap

$$\text{Available Hours} = 572\text{ h}$$
$$\text{Deficit} = 873.48 - 572 = 301.48\text{ h/month}$$

This indicates a serious bottleneck that needs to be fixed. Therefore, if the machine and operator operate as described, the actual working time needed to produce 20,000 units of RAC in a month is 873.48 hours. Nevertheless, there are only 572 hours of working time available. In order to satisfy the demand, an extra 301.48 hours are needed.

3.5.4 Key Findings:

- Only one End-shaping Machine is available.
- The machine cannot simultaneously perform tube expansion and reduction.
- Die changes cause significant downtime.
- The operator may waste time on non-productive activities.
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3.6 Future-State Modeling

Three Future-State improvement options were created based on the bottleneck that was found and the substantial capacity shortfall in the Tube Processing Section. Lean techniques, equipment upgrades, and structural capacity expansion are the various improvement mechanisms that each alternative focus on. In order to estimate achievable performance, the Future-State models were built using capacity calculations, SMED analysis, and VSM principles.

3.6.1 Option A: SMED and Operator Optimization (Lean Improvement Only)

Option A explores whether non-capital, process-focused improvements can sufficiently increase capacity. This option incorporates:

- **SMED application** to reduce die-change time by reorganizing internal and external setup activities

- **Batch optimization**, lowering the number of batch switches and associated changeovers
- **Operator efficiency improvements** through standardized work and reduced walking and rehandling

These assumptions are based on established lean and SMED literature, where 40–70% changeover reduction is typical during initial implementation. A conservative improvement set was used:

- 50% reduction in die-change time
- 20% reduction in number of die changes
- 10% operator efficiency gain

The Future-State VSM for Option A reflects:

- Reduced setup blocks
- Smoother operator flow
- Improved cycle-time alignment
- Lower machine idle periods

Modeled outcome:

$$\text{Total Required Hours} = 768.66 \text{ h/month}$$

The section still falls short of the 572 available hours even though the required hours have significantly decreased, suggesting that Option A by itself cannot remove the bottleneck but could be a supporting improvement if machine investment is chosen.

3.6.2 Option B: Replacement with a High-Throughput Machine

Option B evaluates installing a new, higher-speed tube-processing machine, which the company is already considering. The expected benefit is:

- Lower cycle times for both expansion and reduction
- Automated or minimal-changeover tooling, eliminating die-change losses
- Higher consistency and reduced downtime.

A capacity feasibility model was applied to identify the minimum performance the new machine must achieve. Considering present processing requirements (838.54 hours/month), the new machine must reduce cycle times such that:

$$\text{Required Hours}_{new} \leq 572 \text{ h/month}$$

The table below shows the results of the capacity sensitivity analysis for Option B. It shows how different amounts of cycle-time reduction affect the total machine-hours needed to meet monthly demand. The Table 3 shows the minimum performance improvement needed for the new high-throughput machine to get rid of the bottleneck by comparing these projected needs to the fixed monthly availability of 572 machine-hours. This analysis provides critical input for evaluating the feasibility of Option B and determining whether a single upgraded machine can reliably satisfy production requirements.

Table 3: Results of performance improvement vs required hours:

Cycle-Time Reduction	Required Hours (approx)	Meets Demand?
10%	754 h	❌ No
20%	670 h	❌ No
25%	629 h	❌ No
30%	587 h	❌ Almost
32%	**572 h**	**✓ Yes**
35%	545 h	✓ Yes

This corresponds to a necessary:

$$\approx 32\% \text{ reduction in total processing time}$$

The Future-State VSM for Option B shows:

- A single streamlined flow
- No setup blocks (eliminated die change)
- Significantly shorter cycle times
- Smooth pull-based scheduling

Modeled outcome:

If the machine delivers ≥32% faster rate,

$$\text{Total Required Hours} \approx 572.47 \text{ h}$$

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which meets monthly demand. Thus, Option B is feasible, contingent on equipment specifications. Then one new machine alone can meet monthly demand if vendor machine reduces cycle time ≥32% and machine eliminates die changes completely.

3.6.3 Option C: Two Machines Operating in Parallel
Option C represents structural capacity expansion through adding a second machine identical to the existing one. Workload is divided equally between the two machines, effectively doubling the processing capability. Assumptions include:

- Equal distribution of expansion and reduction workloads
- The die-change time remains constant
- One operator may be assigned to each machine or cross-operate based on facility policy

The modeled processing hours are:

$$419.27 \text{ h (processing)} + 34.94 \text{ h (die changes)} = 454.21 \text{ h/month}$$

This comfortably satisfies the available 572 hours and provides a capacity buffer of ~118 hours for future scaling, variability, or unplanned downtime. Option C is the most robust solution but also the most capital-intensive.

4. Result & Discussion

In order to assess the value of the three improvement alternatives under consideration, the total machine-hours of activity for each of the three alternatives were calculated based on the Future-State VSMs and capacity models. The results measure the extent to which each option cuts down the current capacity deficit and whether each option is sufficient to meet the monthly production requirement of 572 available machine-hours. A comparative summary is presented below showing performance of Option A, B and C in terms of the hours required, elimination of bottlenecks and practical feasibility (Table 4).

Table 4. Comparative Summary Table

Option	Key changes	Required hours (h/month)	Meets demand?
Baseline	Current machine	**873.48**	No (−301.48 h)
A	SMED + batching + operator (no CAPEX)	**768.66**	No (−196.66 h)
B	New high-throughput machine (≈32% faster, no die changes)	**≈572.47**	Yes (~meets)
C	Two machines in parallel	**454.21**	Yes (comfortably)

The analysis of the Room Air Conditioner (RAC) manufacturing line clearly shows that the Tube Processing Section specifically the End shaping machine is the main constraint in the overall plant throughput. While all upstream and downstream stations have adequate capacity, the Tube Processing Section are in need of 873.48 hours processing time per month while they have only available 572 hours, leaving a significant deficit in the availability of 301.48 hours processing time per month. This quantifiable gap confirms the observed shortfalls in monthly production are the result of structural limitations within the work station as opposed to scheduling, labor assignment, or demand variance.

A major conclusion is, therefore, that the bottleneck involves not a single inefficiency, but rather a combination of high cycle times, frequent changes between dies and operator-related delays. The machine is not capable of processing expansion and reduction at the same time which forces sequential batching. The results of time study 13.01 seconds per expansion and 28.2 sec per reduction become increasingly burdensome as within the month of 154,000 expansion tubes and 36,000 reduction tubes are required. When compounded with the frequent die changes happening 12 times per shift the effective capacity of the machine is eroded severely. These losses are consistent with the common high mix, batch-based environments where setup time is the primary constraint on machine availability and therefore one of the limitations on throughput.

The evaluation of three improvement scenarios gives an insight into the nature of the bottleneck. Option A which applies the technique of SMED, batching improvements and operator optimization requires a total time of 768.66 hours but still leaves a shortage of 196.66 hours in the available capacity. This shows that whilst improvements based on lean can solve the problem at routes, they are not sufficient where the root cause of the waste is to be solved where there is a structural mismatch between demand and machine capability. The result is consistent with attractive literature on SMED indicating that SMED can significantly lower setup losses and cannot address fundamental limitations in throughput when demand is much higher than machine capacity.

Option B which is replacement with a high throughput machine helps to identify the minimum technological performance required to achieve capacity stability. Modeling shows that the new machine must provide some minimum of 32% improvement in cycle time in order to reduce processing hours to the necessary level of 572 hours. While a solution that is technically possible, this approach relies heavily on the specifications of the vendor and assumes that die-change losses will be completely eliminated through automation. This brings introduction of risk because of real world performance which can vary on tooling, skill of operator, maintainability.

In contrast, Option C of adding a second machine parallelly provides the most robust and reliable option. The distributed workload results in the total number of required hours being 454.21, so it has a buffer of roughly 118 hours against variability, unplanned downtime or future demand growth. From the aspect of operations management, this option not only removes the bottleneck but also makes the system more resilient and scalable. Although capital-intensive, the parallel machine approach eliminates the dependence on aggressive cycle time improvements, as well as reduces operational risk.

The findings suggest that the Tube Processing Section constitutes a traditional structural bottleneck rather than an issue of process waste. The analysis indicates that Option C offers the most practical long-term solution, whereas Option B may be viable only if performance guarantees are fulfilled. These insights reinforce the company's proposed investment strategy and offer a robust engineering foundation for the selection of capacity-enhancement options.

5. Conclusions

This study systematically examined the production deficiencies in a Room Air Conditioner (RAC) manufacturing line and identified the Tube Processing Section as the primary bottleneck limiting monthly output. Through comprehensive time analysis, Value Stream Mapping, SMED evaluation, and capacity modeling, the section was determined to necessitate 873.48 hours of processing time monthly, significantly surpassing the 572 available machine-hours and resulting in a critical capacity shortfall of 301.48 hours. This deficiency arises from prolonged cycle times, sequential processing limitations, frequent die alterations, and delays attributable to operators.
Three enhancement scenarios were assessed to mitigate the bottleneck. Option A, which employs lean methodologies such as SMED and operator optimization, diminished non-value-added time but proved inadequate to rectify the shortfall, affirming that process enhancements alone cannot satisfy demand. Conversely, Option B (a high-throughput replacement machine) and Option C (two machines functioning in parallel) were determined to be viable solutions. Option B resolves the bottleneck provided the new machine achieves a minimum 32% reduction in cycle time, presenting a more economical route to capacity restoration. Option C yields the most favorable result, decreasing the necessary hours to 454.21 and generating a significant capacity buffer, albeit necessitating a higher capital investment.

The study concludes that expanding structural capacity is essential to fulfill monthly RAC production demands. Both Option B and Option C are feasible strategies, with the selection contingent upon investment capacity, performance reliability, and long-term scalability objectives. This research employs an integrated VSM–SMED–capacity modeling framework that offers a robust, data-driven foundation for future decision-making and acts as a practical guide for eliminating bottlenecks in high-mix, labor-intensive manufacturing settings.

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