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Hybrid-Intelligence Lean Six Sigma for Error-Proof Part Supply: Graph Neural Networks and Multiobjective Optimization

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Reducing Part-Supply Errors and Labour Waste in Linear Actuator Assembly Using DMAIC

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Abstract

Purpose: This study aims to eliminate part-supply errors, reduce non-value-added labour, and improve ergonomic conditions in high-mix single-axis linear actuator assembly using the DMAIC methodology. *Methods*: A DMAIC-based case study was conducted in a Vietnamese precision-component manufacturing plant. Pareto analysis, process observation, 4M Ishikawa diagrams, on-site verification, and cause-prioritization matrices identified three root causes from seven candidates. Five improvement solutions were implemented, including single-order kitting, a two-level tray conveyor, centralized automatic ball feeding, point-of-use parts storage, and barcode-based poka-yoke verification. *Results*: Missing and incorrect parts accounted for 76% of assembly part defects, with an initial supply-error rate of 0.31%. Supply errors decreased from 6.33 per month to zero during the post-improvement verification month ($p \approx 0.0018$). Ball insertion time decreased by 1.13 minutes per cycle, while non-value-added labour was reduced by 3,203 hours annually. The improvements generated annual savings of US$7,110 from a US$5,200 investment, achieving an 8.8-month payback period and a first-year return on investment of approximately 37%. *Value*: This study demonstrates a cost-effective, human-centred DMAIC approach integrating error-proofing, material-flow redesign, and ergonomic improvements to enhance assembly quality, operational efficiency, and sustainable manufacturing practices.

Keywords: Lean Six Sigma; DMAIC; Part-supply errors; Poka-yoke; Ergonomic improvement.

1 Introduction

Manufacturers of factory-automation components work in a market with high product variety, short delivery times and strong price pressure. Single-axis linear actuators are a typical example. One catalogue family can contain many strokes, leads, motor brackets and covers, and most orders are small. For this reason, the final assembly is still mostly manual, and the line receives a different set of parts for almost every order. In such a high-mix environment, the quality of the product depends not only on the assembly operation itself but also on the material supply that feeds the line. When a wrong part or a missing part reaches the assembly table, the operator must stop, disassemble and repeat the work, and a defect may also escape to the customer.

The literature on assembly line feeding shows that the choice of feeding policy, the location of stores and the way of presenting parts strongly influence the total cost of an assembly system [20, 21]. Kitting moves the part search away from the assembly operator and brings the parts close to the assembly object, but the benefit depends on which parts are kitted and how the kit is matched with the assembly sequence [20]. Kitting also creates new error possibilities, because every kit is a small order-picking job. Caputo et al. [22] modelled the probability and the cost of errors along the whole chain from picking in the warehouse to assembly, and showed that each error source has its own contribution to the quality cost. Fager et al. [23] found that the picking information system is crucial for kit preparation efficiency, and Setayesh et al. [25] identified physical workload, fatigue, complexity, memory demand and vision as failure modes that create pick errors in manual order picking.

Human factors are therefore central. Grosse et al. [24] argued that planning models which ignore the worker are only partly realistic, and Neumann et al. [26] showed that technology projects fail when changes in worker demands are not considered. In many Vietnamese electronics and mechanical assembly plants the workforce is young and mostly female, so pregnancy at work is a normal situation. Clinical guidance recommends limiting lifting and repetitive bending for pregnant workers [27]. Squatting to pick parts from low shelves and pushing heavy trolleys between stores are exactly the motions that such guidance tries to reduce. An improvement project in this type of plant should consequently reduce errors and physical load at the same time.

Six Sigma, and its improvement cycle DMAIC, gives a structured, data-driven sequence for this kind of problem [3, 4]. Challenging goals combined with a structured method improve project performance [5], and the method has been used for cost reduction in many industries [6]. Many applied case studies report clear results. Barbosa et al. [8] raised the quality rate by 41% in tyre production. Rifqi et al. [7] reduced work-in-progress by 90% in an automotive plant. Pereira et al. [10] improved OEE by 20% in the mould industry. Koch et al. [2] and Silva et al. [1] reduced cable waste in Bowden cable lines, with material savings of 37.5% on the highest-volume line and a payback time of about three months. In logistics processes, Khan et al. [28] used DMAIC in a courier warehouse and increased picker throughput from 42 to 59 items per hour, and Fares et al. [29] reported a 30% efficiency gain in manual picking and packing. Pombal et al. [17] reduced the time to locate consumables by about 70% with visual management. Table 1 summarises the studies that are closest to the present work.

Table 1 Summary of applied DMAIC and Lean studies related to material handling and assembly

Study	Context	Main tools	Reported result
Rifqi et al. [7]	Automotive plant, Morocco	DMAIC, VSM, 5S	WIP −90%, turnaround −21%
Pereira et al. [10]	Mould industry, CNC	LSS, Pareto, PDCA	OEE +20%
Pereira et al. [11]	Brake cable assembly line	A3 + DMAIC	Productivity +49%, cycle time −33%
Ferreira et al. [12]	Wood products	iLeanDMAIC	Set-up 39 → 17 min
Khan et al. [28]	Courier warehouse	DMAIC	42 → 59 items/picker·h
Fares et al. [29]	Manual picking and packing	Lean, NVA analysis	Efficiency +30%
Pombal et al. [17]	Maintenance workshop stores	Visual mgmt, kanban	Search time −70%
Silva et al. [1]	Bowden cable lines	DMAIC, t-test, ANOVA	Material −37.5%, payback ≈ 3 months
This study	Linear actuator assembly, Vietnam	DMAIC (QC story), poka-yoke, kitting, layout	Supply errors 0.31% → 0; −3,203 h/year

Although these studies are useful, three gaps remain. First, most DMAIC cases focus on machine processes or on warehouses alone; few follow the full path from the store to the assembly table, where the supply error actually appears. Second, the kitting and order-picking literature [22, 23, 25] is mostly based on models, experiments or interviews, and gives limited evidence of shop-floor interventions that remove the error causes. Third, very few applied studies treat the ergonomic condition of the operators, such as a pregnant operator, as a design input of the improvement.

The objective of this article is to eliminate part-supply errors in the LX assembly section of a precision-component manufacturer by applying the DMAIC cycle, and at the same time to reduce the handling and

walking workload of the operators. The study answers three research questions: (RQ1) which root causes create part-supply errors between dispersed stores and a high-mix manual assembly line; (RQ2) which low-cost countermeasures can remove these causes; and (RQ3) what quality, time and economic effects are obtained. The work contributes a complete, reproducible DMAIC case with photographs, layouts and the decision data of each step, which practitioners in similar plants can follow. The remainder of the paper is organised as follows: Section 2 presents the methodology and the product, Section 3 describes each DMAIC step, Section 4 analyses the results, Section 5 discusses them against previous studies and Section 6 concludes.

2 Methodology

2.1 Different steps of the DMAIC cycle: from definition to control

The project was run by a five-member shop-floor improvement team (Q-up circle) with one adviser, from April to August 2019. The company uses a ten-step QC story; Fig. 1 shows how these steps were mapped to the DMAIC phases and which tools were used in each phase.

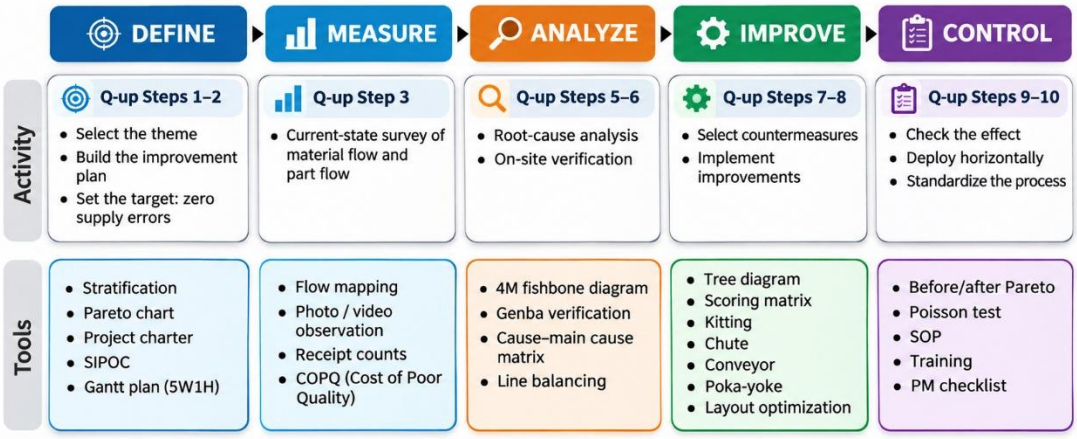


Fig. 1 DMAIC framework of the project, with the company's ten Q-up steps and the tools applied in each phase

In the first step (Define), the quality situation of the section was stratified with Pareto charts; the theme and the target were fixed in a project charter, the process was framed with a SIPOC diagram and a time plan was prepared. The cumulative share used in the Pareto charts is calculated by Eq. (1), where n_i is the number of defects of category i, ordered from the largest, and m is the number of categories.

$$C_k = \frac{\sum_{i=1}^{k} n_i}{\sum_{i=1}^{m} n_i} \times 100\% \tag{1}$$

In the second step (Measure), the material and part flow was observed on site and recorded with photographs, and the frequency and size of part receipts were counted. The baseline performance was expressed as a defect ratio p, as defects per million opportunities (DPMO, Eq. 2) and as a short-term sigma level Z_{ST} with the conventional 1.5σ shift (Eq. 3), where Φ^{-1} is the inverse standard normal function [4].

$$DPMO = \frac{D}{U \times O} \times 10^6 \tag{2}$$

$$Z_{ST} = \Phi^{-1}\left(1 - \frac{DPMO}{10^6}\right) + 1.5 \tag{3}$$

Here D is the number of defects, U the number of units and O the number of opportunities per unit (one in this study, i.e. the supplied set is correct or not). The third step (Analyze) used a 4M fishbone diagram, on-site (genba) verification of every candidate cause and a cause–main cause matrix. In the fourth step (Improve), countermeasures were generated with a tree diagram and evaluated with a scoring matrix. Each countermeasure j receives a rating $r_{jc} \in \{0, 1, 2, 3\}$ on four criteria c (ease of operation, feasibility, lead

time and cost), and the score is the product of the ratings (Eq. 4). The product form means that a countermeasure which is not feasible on any single criterion (rating 0) is excluded automatically.

$$S_j = \prod_{c=1}^{4} r_{jc} \tag{4}$$

In the last step (Control), the effect was checked by a before/after Pareto comparison and by an exact Poisson test, the time savings were converted into money, and standards, training and maintenance were put in place. Annual hours saved H, the monetary saving G, the payback time T_{PB} and the first-year return on investment are given by Eqs. (5)–(7), where h_k is the daily time saving of improvement k, N_d the number of working days per year, w the labour cost rate and I the investment.

$$H = \sum_k h_k \times N_d, \quad G = H \times w \tag{5}$$

$$T_{PB} = \frac{I}{G} \times 12\ (months), \quad ROI_1 = \frac{G-I}{I} \tag{6}$$

Because only monthly defect counts were available, the change in supply errors was tested with an exact Poisson test. If the baseline rate is λ defects per month, the probability of observing $x = 0$ defects in one month by chance is given by Eq. (8); a value lower than 0.05 indicates that the reduction is statistically significant. This test assumes a comparable production volume in the baseline and verification months.

$$P(X = 0|\lambda) = e^{-\lambda} \tag{7}$$

2.2 Characterizing single-axis linear actuators as a component for factory automation

2.2.1 How LX actuators are composed

The LX product is a ball-screw-driven single-axis actuator used to move loads linearly in automatic machines. As shown in Fig. 2, its main parts are the rail (base), the ball screw shaft with its block (slider), the motor bracket, the motor support, the steel balls of the recirculating guide, and a group of small parts such as bearings, washers, screws, and covers. The finished products differ in stroke, size (for example LX20, LX26, LX30 and LX45), motor bracket type and accessories such as covers and sensors. Several of these parts are produced in-house (machined parts kept in the PC-Stock room), while purchased parts such as screws and bearings are kept in the warehouse (WH).



Fig. 2 LX single-axis actuator and its main components (photographs from the assembly section)

2.2.2 How LX actuators are assembled

The assembly follows five sequential steps (Fig. 3): (1) part preparation, (2) ball insertion into the block and rail, (3) assembly of the remaining parts, (4) P-Y (pitching and yawing) check, and (5) final check. The checks at steps 4 and 5 can detect a wrong or missing part, but only after the actuator is already assembled. When this happens, the unit returns to repair, where it must be disassembled and the part replaced, which costs about 1 h of work per set. The supply error also interrupts the flow of the line. In other words, the inspection detects the problem but cannot prevent it, so the improvement has to act at the source, during part preparation [31].

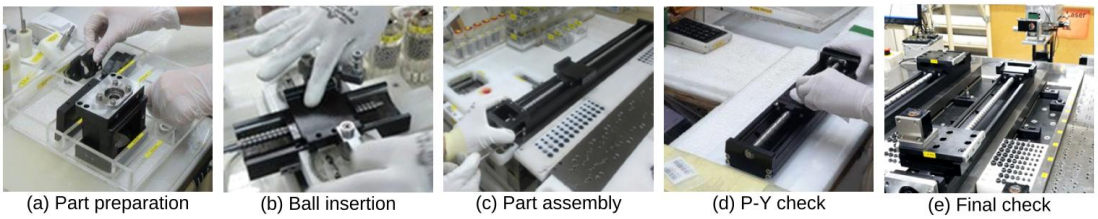


Fig. 3 Five assembly steps of the LX product; a wrong part detected at steps 4 or 5 returns the unit to repair (about 1 h/set)

2.2.3 Area chosen for concept validation

The study was carried out in the LX assembly section (LXA) of a precision-component plant in southern Vietnam, a subsidiary of a Japanese factory-automation components group. The section had twelve manual assembly tables. Parts came from two separate stores, the PC-Stock room and the WH, through a temporary store inside LXA. The improvement was first validated on the LX26/LX30 line and later deployed to the LX20 and LX45 sizes.

3 Problem contextualization and methodological approach

The DMAIC cycle was applied to the part-supply process between the stores and the LX assembly tables.

3.1 First step (Define)

3.1.1 Initial conditions of the problem

Fig. 4 shows the situation before the project. Parts for one LX order were issued from the PC-Stock room and from the WH, delivered to the temporary store of LXA, and checked there against the list. An LXA operator then prepared the parts of several orders at once, put them on a multi-shelf trolley, and pushed the trolley to the assembly tables. Wrong or leftover parts had to be returned to the original store, so there was a continuous back-and-forth of parts between three locations. The preparation work required squatting at low shelves and pushing heavy trolleys.



Fig. 4 Initial conditions: (a, b) two separate stores, (c) assembly table, (d–f) kitting and transport work at LXA before the project

The project was initiated by the operator in charge of part supply, who was pregnant at the time and wanted to solve the return and supply problems before her maternity leave. This personal motivation reflects a wider condition of the plant: the number of pregnant employees rose from 8 in 2018 to 21 in 2019, or from 10% to 23% of the workforce (Fig. 5). Reducing squatting, lifting and walking was therefore treated as a design requirement together with the quality target.

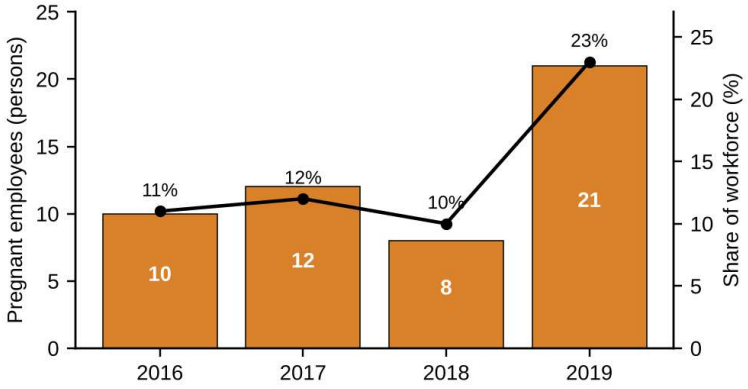


Fig. 5 Number of pregnant employees and their share of the workforce in the plant, 2016–2019

3.1.2 Theme selection and target

The quality data of January–March 2019 were stratified (Fig. 6). Of the 36 part defects recorded in the plant, 25 (69%) were found at LX assembly, compared with 8 in machining and 3 at incoming quality control (IQC). Among the 25 defects at LX assembly, missing parts (14) and wrong parts (5) together represented 76%, while scratches (4) and chipped edges (2) were the rest. The FY18 data confirmed the same picture: the ratio of defects caused by part supply was 0.31%, against 0.07% for scratches and 0.03% for chipped edges. The team therefore concluded that the part-supply operation had to be upgraded and set the target "zero part-supply errors" by September 2019.

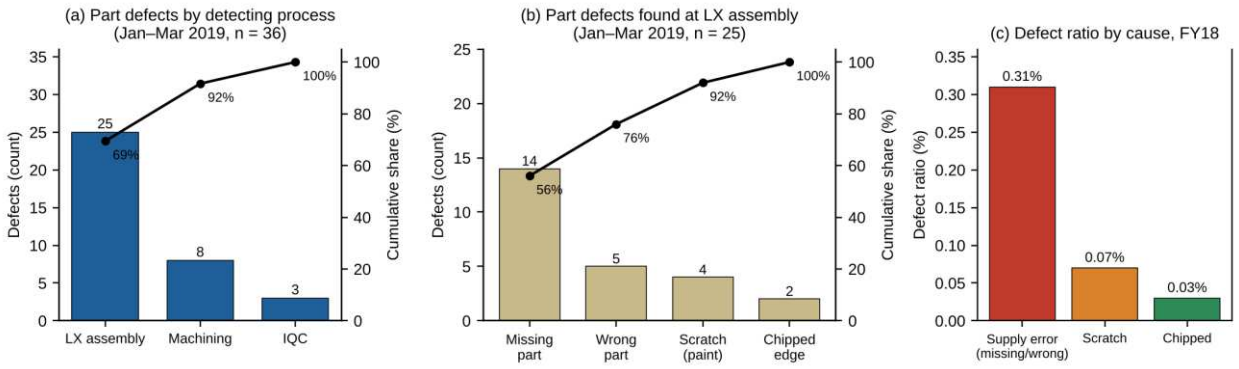


Fig. 6 Stratification used to select the theme: (a) part defects by detecting process, (b) part defects at LX assembly, (c) FY18 defect ratios by cause

The project charter and the SIPOC diagram are summarised in Table 2.

Table 2 Project charter and SIPOC of the part-supply process

Element	Content
Problem statement	Missing/wrong parts are 76% of part defects at LX assembly (Jan–Mar 2019); FY18 supply-error ratio 0.31%
Goal (CTQ)	Zero part-supply errors at LXA by September 2019; reduce handling and walking of operators
Scope	From part issue at PC-Stock/WH to delivery of the part set to the LX assembly table

Element	Content
Team	Five-member Q-up circle (leader + four members) and one adviser
Suppliers	PC group (production control), PC-Stock room, WH, engineering (PE)
Inputs	Production orders (PO), parts lists, in-house and purchased parts, steel balls
Process	Issue → receive and check at LXA → kit → transport to table → assemble → P-Y and final check
Outputs	Correct and complete part sets; assembled LX actuators
Customers	LX assembly operators (internal); shipping and end users (external)

3.1.3 Project plan

The activity plan followed the QC story from April to August 2019 (Fig. 7). The longest step was the implementation of countermeasures (June–July), because it included the design and manufacture of jigs and conveyors in house. The actual progress followed the plan closely.

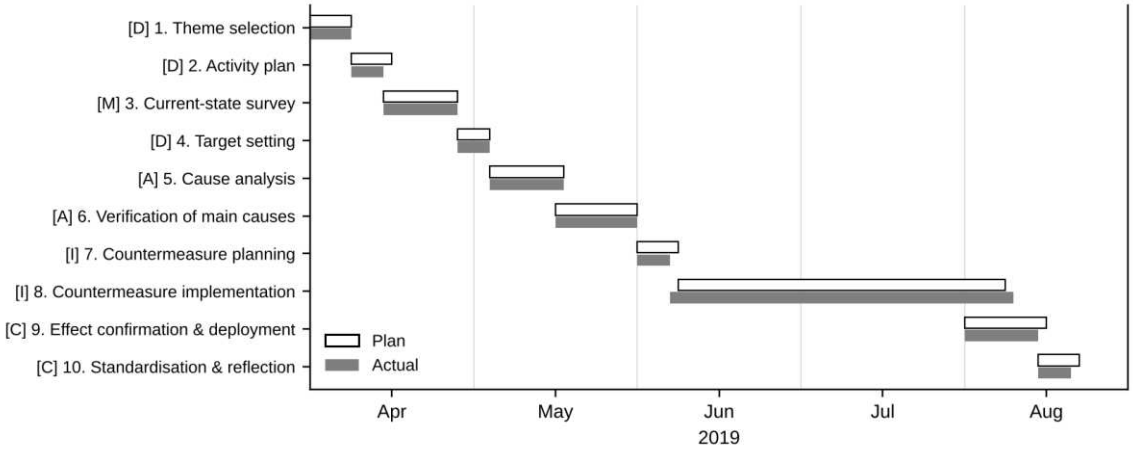


Fig. 7 Project plan and actual progress, April–August 2019 (letters indicate the DMAIC phase)

3.2 Second step (Measure)

At this stage of the DMAIC cycle, data were collected to describe the current part-supply process and its performance.

3.2.1 Data collection plan

Table 3 shows the data collection plan. The main indicator was the number of part-supply errors (missing and wrong parts) found at LXA per month. Secondary indicators were the frequency and quantity of part receipts and the time spent on checking, delivery, preparation, in-line transport and ball insertion.

Table 3 Data collection plan

Indicator	Source	Method	Period
Part defects by category	Quality records of LXA, machining, IQC	Stratification, Pareto	Jan–Mar 2019; FY18
Receipts per day and parts per receipt	PC-Stock and WH delivery to LXA	Direct counting	Apr–May 2019
Flow of parts and people	LXA, PC-Stock, WH	Observation, photographs, layout drawings	Apr–May 2019

Indicator	Source	Method	Period
Time per activity (h/day)	Operators of LXA and stores	Time observation before/after	Apr–Aug 2019
Repair loss	Repair records	Average time per repaired set	FY18–2019

3.2.2 Current state of part supply

The current-state survey mapped the flow shown in Fig. 13a. In-house LX parts and ball-screw sub-assemblies were stored in the PC-Stock room, purchased parts in the WH, and both were sent to a temporary store inside LXA. Parts from PC-Stock arrived 8 times per day with an average of 48 pieces per receipt, so about 384 pieces per day had to be received and checked from this store alone. Parts from the WH arrived on a mixed trolley with an average of 955 pieces per receipt. All checks were visual, against a printed parts list. The preparation operator then built kits for several orders at the same time and pushed the trolley to the twelve tables.

3.3 Current state measurements

With the FY18 supply-error ratio of 0.31%, Eq. (2) gives about 3,100 DPMO (one opportunity per supplied set), which corresponds to a short-term sigma level of about 4.24 by Eq. (3). In January–March 2019, 19 supply errors were found at LXA, a mean of $\lambda = 6.33$ errors per month. Each error led to about 1 h of repair, plus the interruption of the line. The line-balance chart prepared by the team (Fig. 8) also showed that ball insertion was the bottleneck station: about 6.3 min per set against about 3.8–3.9 min at the other stations, because the operator had to walk to fetch and count balls.

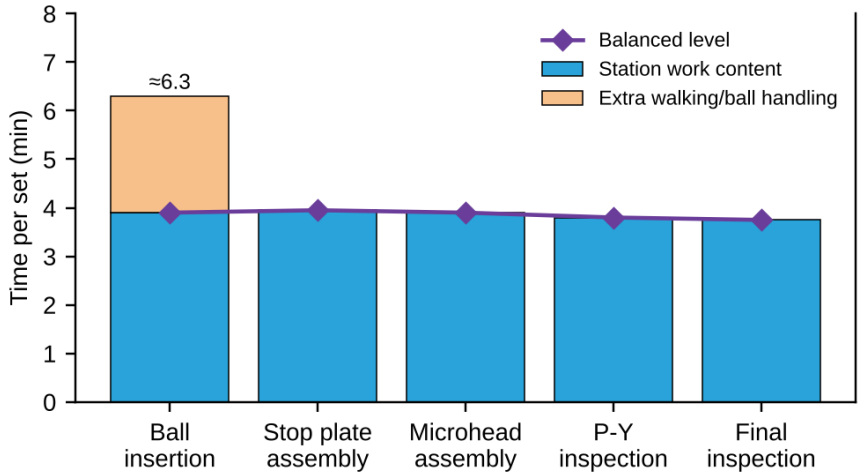


Fig. 8 Average assembly time per set by station (SS stage 60); the ball insertion station exceeded the balanced level because of walking and ball handling (values read from the team's chart, approximate)

3.4 Third step (Analyze)

At this stage, the data and the observations were analysed to find the root causes of part-supply errors.

3.4.1 Process analysis

The team built a 4M fishbone diagram (Fig. 9). Under Machine, it listed old and heavy trolleys, a printer giving faint parts lists and visual checking as the only control. Under Method, it listed kitting of several types at once, frequent type changes, look-alike parts of different types, parts kept in several stores and checking only by the PO list. Under Man, it listed picking errors of WH and PC-Stock staff, received parts not checked and loss of concentration. Under Material, it listed many receipts per day, a large daily quantity,

faint printing and the absence of a judgement standard at receipt. Seven candidate causes (C1–C7) were selected for verification on site.

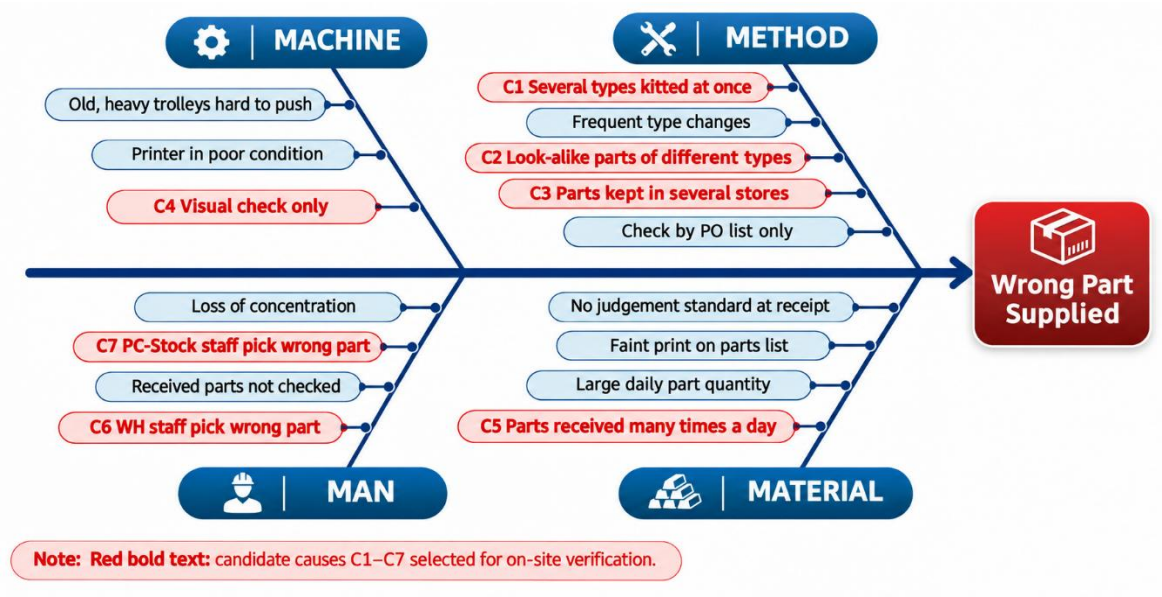


Fig. 9 4M cause-and-effect diagram for "wrong part supplied"; C1–C7 are the candidate causes verified on site

3.4.2 On-site verification of the candidate causes

C1 – Several types kitted at once. The operator confirmed the order, picked the parts, and put them on the trolley for several orders in one batch (Fig. 10a–d). Because many part types were handled at the same time, the risk of picking a part for the wrong order was high.

C2 – Look-alike parts of different types. Motor brackets and supports of different types had the same size and almost the same shape (Fig. 10e, f). The difference was only in small details, which is a known failure mode for visual picking [25].

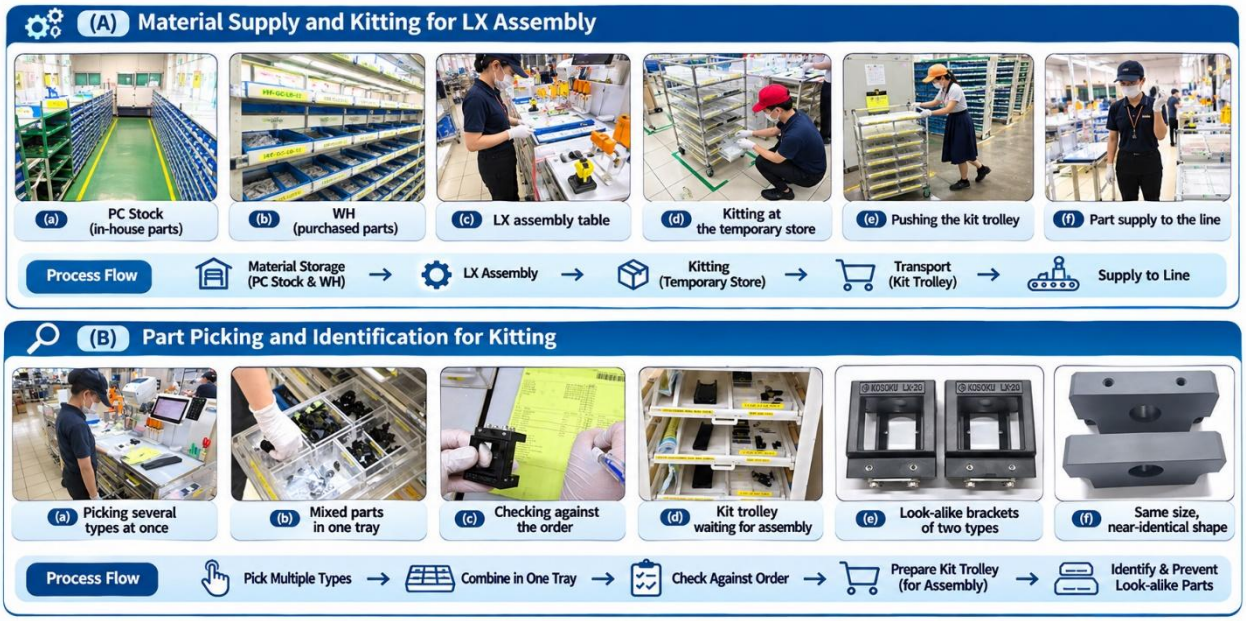


Fig. 10 Verification of C1 (several types kitted at once, a–d) and C2 (look-alike parts, e–f)

C3 – Parts kept in several stores. LX parts were distributed over three areas: the PC-Stock room, the WH and an extension of the PC-Stock room (Fig. 11a–c). The long distances made the work tiring, and every additional store added a hand-over and a check.

C4 – Visual check only. At PC-Stock, at the WH and during kitting, the part was confirmed by eye against a paper list (Fig. 11d–f). No device prevented a wrong part from passing.

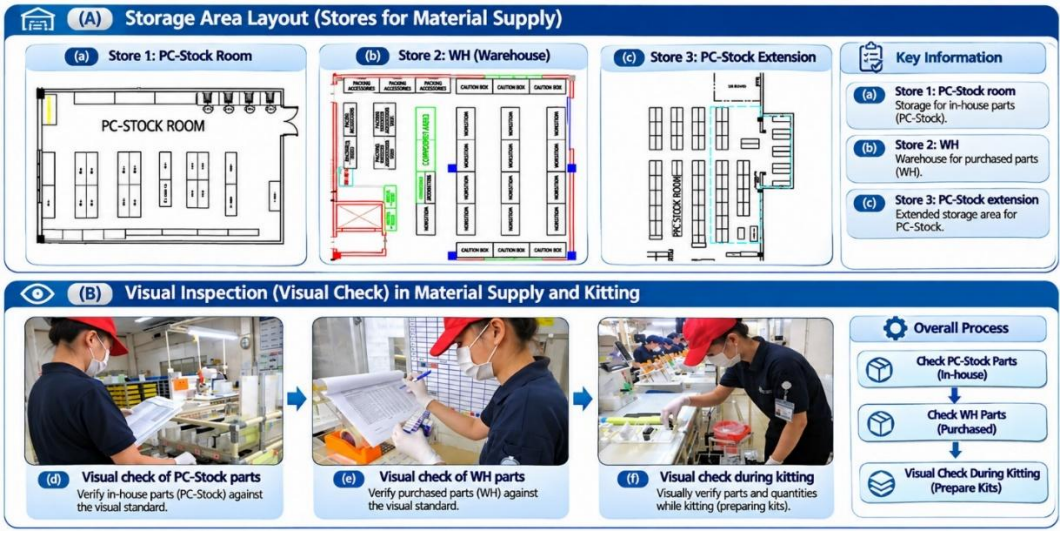


Fig. 11 Verification of C3 (three separate stores, a–c) and C4 (visual checks at three points, d–f)

C5 – Parts received many times a day. As measured in Section 3.2.2, PC-Stock delivered 8 times per day and the WH delivered large mixed trolleys of 955 pieces on average (Fig. 12a, b). The operator often squatted to check parts on the lower shelves.

C6 and C7 – Picking errors at the WH and PC-Stock. Both stores picked parts according to the PO and the list received from the PC group and checked them after picking (Fig. 12c–f). The result depended entirely on the judgement of the person.



Fig. 12 Verification of C5 (receipt frequency, a–b) and C6/C7 (picking at the WH and PC-Stock by paper list, c–f)

3.5 Measurement data analysis

After the verification, the seven candidate causes were related to the problem through a cause–main cause matrix (Table 4). The analysis grouped them into three main causes: (MC1) kitting several product types at once is confusing; (MC2) parts are received and issued many times; and (MC3) there is no control tool. MC3 is supported by four of the seven causes, which shows that the process relied on human attention instead of on an error-proof system.

Table 4 Cause–main cause matrix (● = the verified cause supports the main cause)

Main cause	C1 Several types at once	C2 Look-alike parts	C3 Several stores	C4 Visual check	C5 Many receipts	C6 WH picking	C7 PC-Stock picking
MC1 Kitting several types at once	●					●	
MC2 Parts issued/received many times			●		●		●
MC3 No control tool	●	●		●		●	

3.6 Fourth step (Improve)

At this stage, countermeasures were generated for each main cause with a tree diagram and evaluated with the scoring matrix of Eq. (4) (Table 5). Ratings were ◎ = 3 (highly feasible), ○ = 2 (feasible), △ = 1 (fairly feasible), and × = 0 (not feasible). Two ideas received a zero score and were rejected: grouping similar types to kit together, because it did not remove the confusion, and raising the judgement skill of operators, because it would still depend on people. Three countermeasures obtained the maximum score of 36 and one obtained 18; all four were implemented. During implementation, the team also met new problems (heavy trays, empty-tray return and walking for ball insertion) and solved them in successive loops, as described in Section 3.7.

Table 5 Countermeasure evaluation matrix (score = product of the four ratings)

Main cause	Countermeasure	Operation	Feasibility	Lead time	Cost	Score	Decision
MC1	Group similar types and kit them together	△ (1)	× (0)	○ (2)	◎ (3)	0	Rejected
MC1	Kit one PO (one set) at a time	○ (2)	◎ (3)	◎ (3)	○ (2)	36	Adopted
MC2	Change the store layout	◎ (3)	◎ (3)	○ (2)	○ (2)	36	Adopted
MC2	Connect preparation and assembly	◎ (3)	◎ (3)	○ (2)	△ (1)	18	Adopted
MC3	Raise judgement skill of operators	△ (1)	× (0)	◎ (3)	△ (1)	0	Rejected
MC3	Part-issue control program (Navi)	◎ (3)	◎ (3)	○ (2)	○ (2)	36	Adopted

Fig. 13 compares the part flow before and after the improvements. The new flow removes the temporary store and the batch kitting, brings the LX parts next to the line, adds an electronic check at the point of issue and replaces manual transport with chutes and a conveyor.

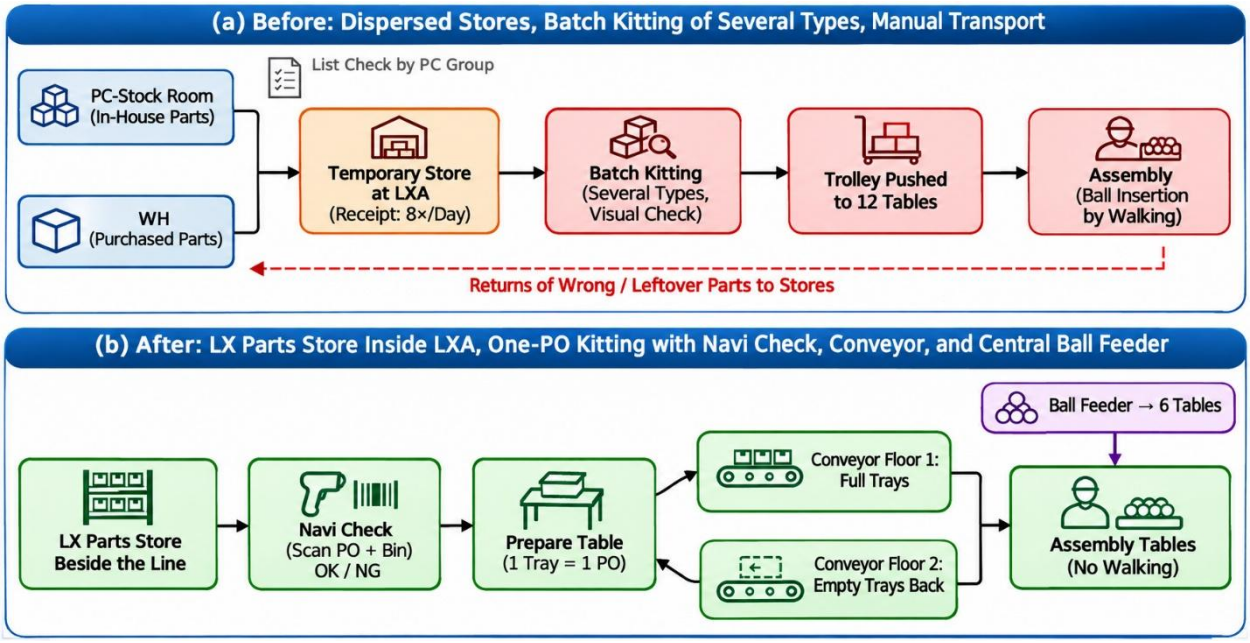


Fig. 13 Part-supply flow (a) before and (b) after the improvement

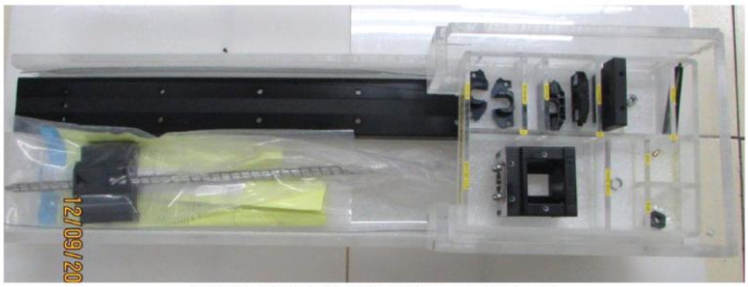
3.7 Definition and implementation of improvements

3.7.1 One-order (one-set) kitting

Before the change, parts from the PC-Stock trolley were combined with parts kept at LXA, and the trays for different types were placed on one trolley (Fig. 14). Three error modes were observed: errors during preparation, placing a tray in the wrong position on the trolley, and taking the wrong tray for assembly. The new rule is that one transparent tray holds all the parts of one PO (one set) and only one PO is prepared at a time (Fig. 15). Since only one set is open at any moment, a part of another type cannot enter the tray, and a missing part is visible at once in the dedicated position.



Fig. 14 Kitting before the change: (a, b) trolleys from PC-Stock and LXA, (c–e) multi-type trays

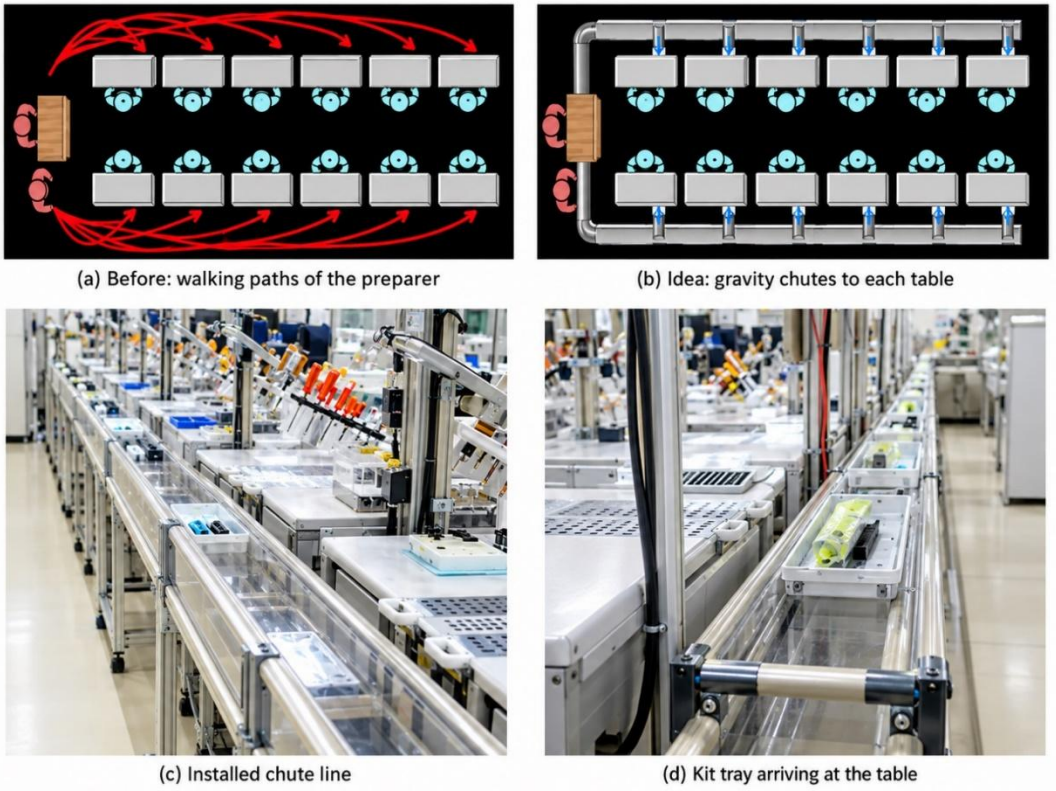


(a) After: one transparent tray holds one PO (1 set)

Fig. 15 After the change: one tray contains the complete set of one PO

3.7.2 Chutes to the assembly tables

One-set kitting increased the number of trays, and the preparer had to carry heavy trays to the twelve tables, which was tiring (Fig. 16a). The team asked: "How can we deliver the tray without carrying it?" The idea was a gravity chute from the preparation table to each assembly table (Fig. 16b). After installation, trays slid by themselves to the tables; the operators no longer carried trays by hand, and the preparation time decreased (Fig. 16c, d). A remaining problem was that the empty trays still had to be collected by hand.



(a) Before: walking paths of the preparer

(b) Idea: gravity chutes to each table

(c) Installed chute line

(d) Kit tray arriving at the table

Fig. 16 Chute concept: (a) walking paths of the preparer before, (b) idea, (c, d) installed chutes

3.7.3 Two-level tray conveyor

To return the empty trays automatically, the transport system was redesigned as a two-level conveyor (Fig. 17). Level 1 carries the full tray from the prepare table to the assembly table, and level 2 carries the empty tray back. With this design, parts are supplied automatically to the table, and empty trays are collected automatically (Fig. 18). The operator, however, still had to walk to fetch and count steel balls.

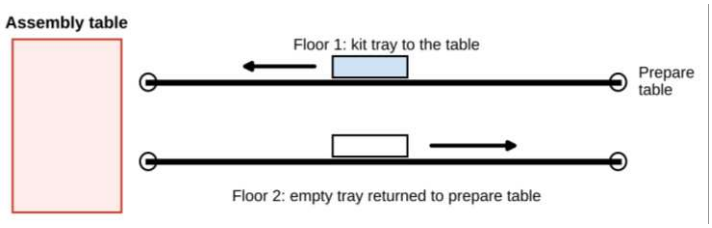


Fig. 17 Concept of the two-level conveyor: level 1 feeds kit trays, level 2 returns empty trays

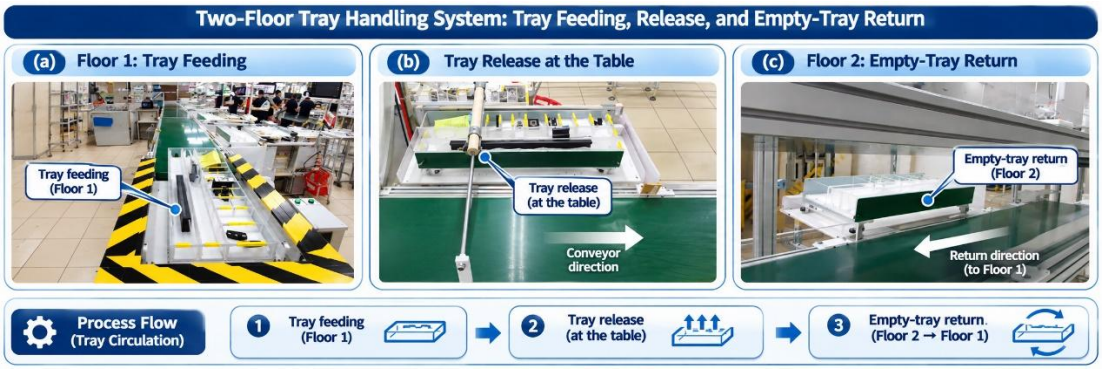


Fig. 18 Installed two-level conveyor: (a) feeding level, (b) tray release at the table, (c) empty-tray return

3.7.4 Central automatic ball feeder

Each LX block needs a defined number of steel balls of a defined size. For example, the LX30-B block needs 36 balls and the LX30-S block 23 balls, dispensed in portions of 4 and 5 balls. The first design had three functions: a size selector, a counter for 4 or 5 balls, and an automatic insertion jig (Fig. 19a–c). However, installing one machine at each of the twelve tables was too expensive. Two alternatives were studied: a mobile machine moving along the line (idea 1) and one central machine feeding several tables (idea 2). Idea 1 still required walking and long insertion distances, while idea 2 required a ball distribution mechanism for each table. Idea 2 was chosen.

The feasibility of idea 2 was verified in two steps. In step 1, a 15 m conduit, longer than the 10 m assembly line, was tested to confirm that balls could travel the required distance (Fig. 19d). In step 2, a distribution mechanism with six outlets and two ball sizes (sizes 26 and 30) was designed and built (Fig. 19e, f). After the improvement, operators no longer walked for ball insertion, and the ball insertion time decreased by 1.13 min per cycle.

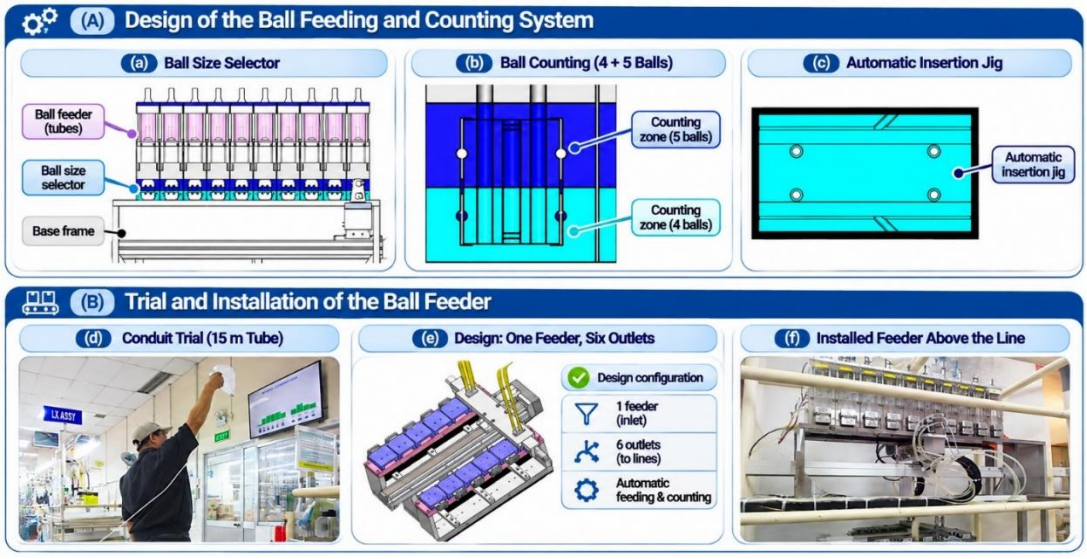


Fig. 19 Automatic ball feeding: (a–c) first design, (d) conduit trial, (e) design with one feeder and six outlets, (f) installed feeder

3.7.5 Relocation of LX parts into the assembly area

To remove MC2, all LX parts were moved from the WH and the PC-Stock room to a new store beside the LX assembly line (Figs. 20 and 21). Parts no longer need to be issued in advance and delivered several times a day; the preparer picks them directly from the shelf next to the preparation table. This also eliminated the temporary store and the return flow.

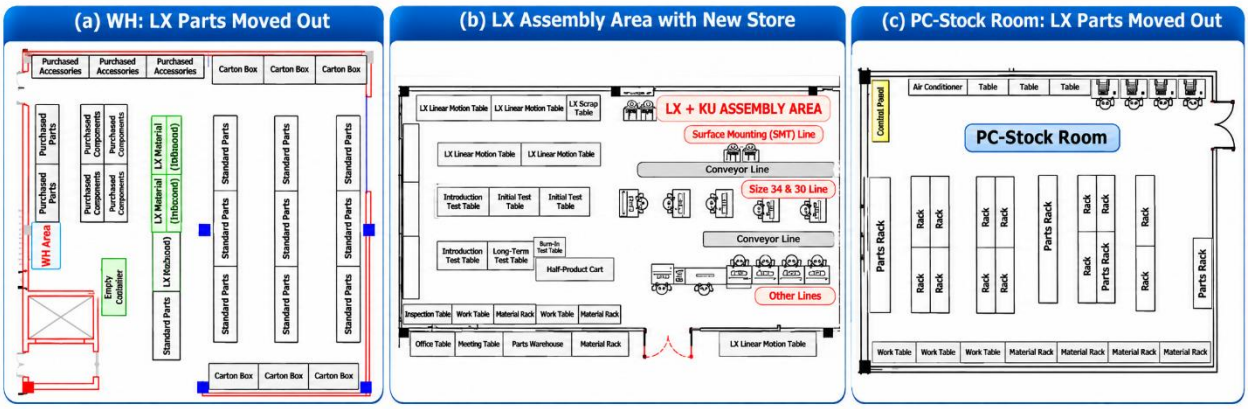


Fig. 20 Layout change: LX parts moved out of (a) the WH and (c) the PC-Stock room into (b) the LX assembly area

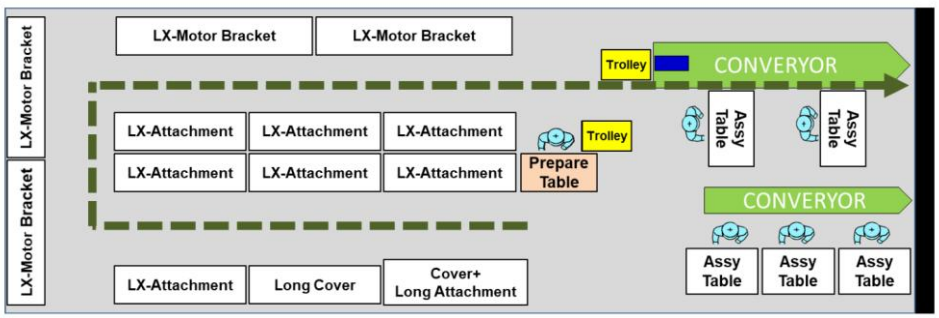


(a) New LX parts store beside the assembly line

Fig. 21 New LX parts store beside the assembly line

3.7.6 Part-flow layout connecting preparation and assembly

The store, the preparation table, the two conveyors, and the assembly tables were arranged as one flow (Fig. 22). Motor brackets, attachments, and long covers are stored in the order of use along the U-shaped path, and trolleys are used only for long parts. The preparation and the assembly are thus linked directly, without intermediate storage.

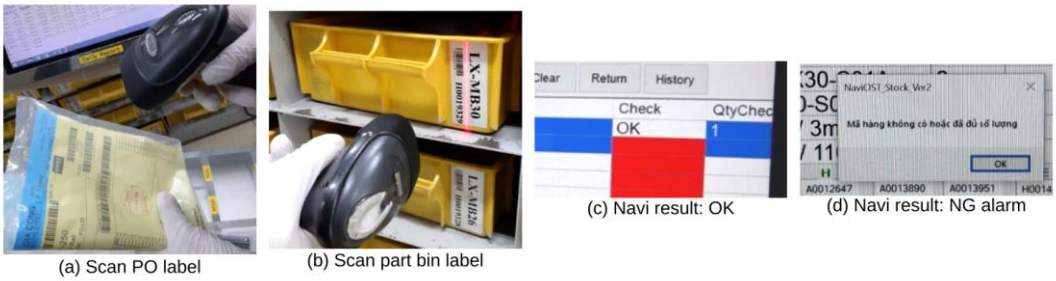


(a) Part flow: prepare table, conveyors and assembly tables

Fig. 22 Part-flow layout of the LX section after the improvement

3.7.7 Navi barcode check at part issue

To give the process a control tool (MC3), a simple navigation program ("Navi") was developed for part issue (Fig. 23). The operator scans the PO label, then scans the label of each bin from which a part is taken. The program compares the bin with the parts list of the PO and shows OK (green) or NG (red, with a message such as "the part is not in the list or the quantity is not enough"). The logic is given in Algorithm 1. It works as a poka-yoke at the source [31]: a wrong part is stopped before it enters the tray, instead of being found after assembly.



(a) Scan PO label (b) Scan part bin label (c) Navi result: OK (d) Navi result: NG alarm

Fig. 23 Navi check: (a) scan the PO, (b) scan the part bin, (c) OK result, (d) NG alarm

Algorithm 1 Logic of the Navi part-issue check

Step	Pseudocode
1	Input: PO barcode; bill of materials BOM(PO) = {(part, qty)}
2	picked ← ∅
3	while picked ≠ BOM(PO) do
4	scan bin label → part p, quantity q
5	if p ∉ BOM(PO) or picked[p] + q > BOM(PO)[p] then show NG (red), sound alarm, block next scan until p is returned
6	else picked[p] ← picked[p] + q; show OK (green)
7	end while
8	release tray to conveyor level 1; record PO as complete

3.8 Final step (Control)

3.8.1 Action plan

The final step fixed the improvements in standards (Table 6, Fig. 24). Operators were trained in the new issuing system and in the use of the conveyor and the ball feeder; the issuing instruction for LXA was revised for the new layout, and engineering (PE) introduced a monthly check of jigs and machines. Training records and the instructions are kept at the line.

Table 6 Prevention and standardisation actions

Action	PIC	Method	Date
a. Train operators on the new issuing system (Navi)	Store/LXA leader	Instruction on the new issuing system	20 Aug 2019
b. Train operators on the conveyor and ball feeder	Store/LXA leader	Operating instruction for conveyor and feeder	30 May 2019
c. Issue an issuing instruction for LXA	Store/LXA leader	Revise the instruction for the new layout	26 Aug 2019

Action	PIC	Method	Date
d. Periodic check of equipment (once a month)	PE	Check the condition of jigs and machines	30 May 2019

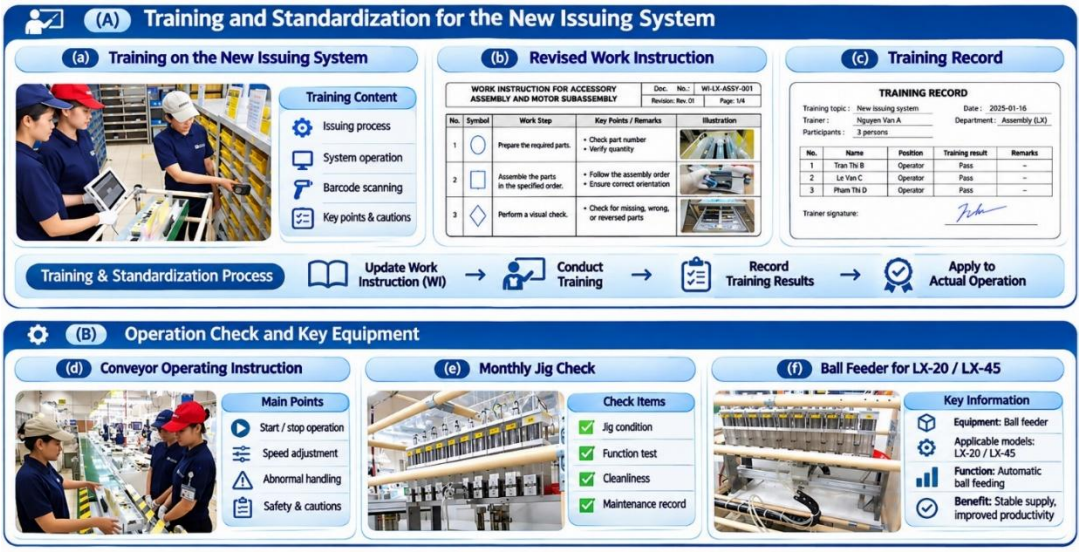


Fig. 24 Control: (a) training, (b) work instruction, (c) training record, (d) conveyor instruction, (e) monthly check, (f) feeder for horizontal deployment

3.8.2 Horizontal deployment

The central ball feeder was planned for the LX-20 and LX-45 sizes in three steps between August and November 2019: manufacture of the machine, verification on one table, and supply of balls to six assembly tables.

4 Results analysis

Fig. 25a compares the part defects found at LX assembly before and after the project. In January–March 2019, there were 14 missing parts and 5 wrong parts (6.33 supply errors per month on average). In September 2019, no supply error was recorded, and the team reached the zero target before the leader's maternity leave. Using Eq. (8) with $\lambda = 6.33$, the probability of observing zero errors in one month by chance is $e^{-6.33} \approx 0.0018$, so the reduction is statistically significant at the 5% level (assuming a similar monthly volume).

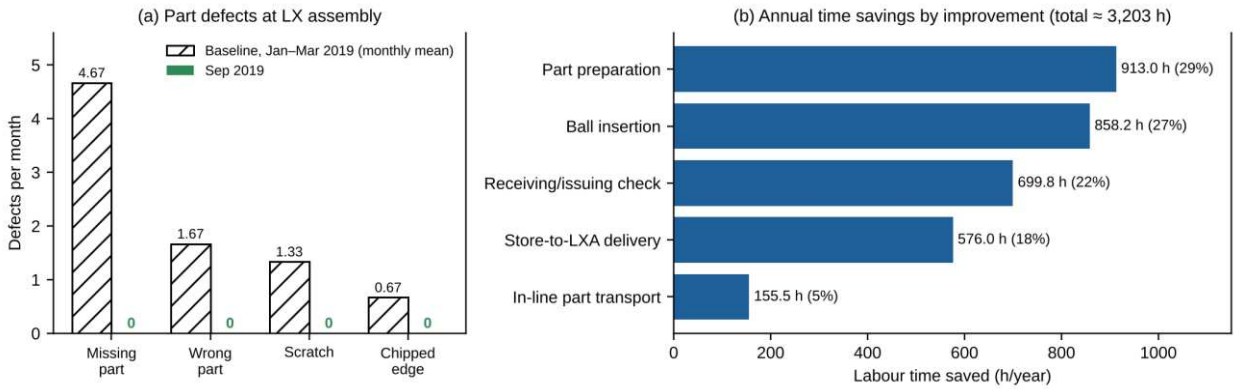


Fig. 25 Results: (a) part defects at LX assembly, baseline monthly mean versus September 2019; (b) annual labour time saved by each improvement

Table 7 lists the time savings. With 288 working days per year (Eq. 5), the five improvements save about 3,203 h per year. The largest contributions come from part preparation (913.0 h, 29%), ball insertion (858.2 h, 27%) and the receiving/issuing check (699.8 h, 22%). The company valued this saving at US$7,110 per year, which implies a labour cost rate of about US$2.22 per hour. The jigs, chutes, conveyor and feeder were designed and built in-house for US$5,200.

Table 7 Time and cost savings after the improvement

#	Item	h/day	h/year
1	Checking time of received/issued parts	2.43	699.8
2	Delivery time from stores to LXA	2.00	576.0
3	Part preparation time	3.17	913.0
4	In-line part transport time during assembly	0.54	155.5
5	Ball insertion time during assembly	2.98	858.2
	Total time saved (1–5)	11.12	3,203
	Annual saving		US$7,110
	Investment (in-house design and manufacture)		US$5,200

With Eq. (7), the payback time is 5,200 / 7,110 × 12 ≈ 8.8 months, and the first-year return on investment is (7,110 − 5,200) / 5,200 ≈ 37%. Over three years, the net saving is about US$16,130, without counting the avoided repair time (about 1 h per error), the avoided line stoppages and the lower risk of a defect escaping to the customer. Besides these numbers, the work content became lighter: squatting at low shelves, pushing heavy trolleys, carrying trays, and walking for balls were removed from the daily routine, and a new operator can take over the issuing work more easily because the Navi check guides each step.

5 Discussion of results

The results confirm that the DMAIC cycle, even in the simple form of a shop-floor QC story, is effective for removing errors in the material supply of a high-mix assembly line. The structure of the project is very similar to the Bowden cable studies of Koch et al. [2] and Silva et al. [1]: a Pareto-based selection of the problem, a careful analysis of the physical process, a series of low-cost devices designed in-house, and a short payback time. In those studies, the main waste was material (cable trim), while in the present study the main waste was hidden labour and the risk of defects; nevertheless, the payback times (about three months and about nine months) are of the same order, and both show that small investments made by internal teams can give a high return.

The main causes found in this study agree well with the error mechanisms described in the literature. Batch kitting of several types (MC1) increases complexity and memory demand, and look-alike parts challenge vision, which are failure modes identified by Setayesh et al. [25]. Caputo et al. [22] showed that errors in kitting can occur at picking, at kit transport, and at use, and the three error modes observed before one-set kitting (wrong pick, wrong tray position, wrong tray taken) correspond exactly to these points. The one-set rule removes the last two, and the Navi check addresses the first. Fager et al. [23] found that the picking information system is crucial for kit preparation efficiency; in this case, the scanning confirmation slightly increases the work per pick, but this cost is more than recovered by removing receipt checks, transport, and returns.

The relocation of parts into the assembly area reflects the trade-off between centralised and decentralised storage discussed by Battini et al. [21]. For a product family with a high variety of parts but a dedicated assembly section, moving the parts to the point of use reduced both the number of hand-overs and the checking time (2.43 h/day). This is consistent with the kitting study of Hanson and Medbo [20], who showed

that the benefit of kitting depends on how the kit is matched with the assembly sequence; here the part-flow layout (Section 3.7.6) arranges the parts in the order of use.

Compared with warehouse DMAIC studies, the gains are similar in nature. Khan et al. [28] increased picker throughput by about 40%, Fares et al. [29] obtained a 30% efficiency gain, and Pombal et al. [17] reduced search time by about 70%. The present study adds a direct quality effect, the elimination of supply errors, because the improvement extended from the store to the assembly table. The ergonomic side is also relevant. Grosse et al. [24] and Neumann et al. [26] argued that integrating human factors improves both performance and worker welfare. In this project, the condition of a pregnant operator was the trigger, and the solutions that reduced bending, lifting, and walking [27] were the same solutions that reduced time and errors.

The study has some limitations. First, the verification period after the improvement was one month; a longer series and a control chart would give stronger evidence of stability. Second, the production volume of each month was not available, so the Poisson test assumes a comparable volume, and the sigma level was calculated with one opportunity per set. Third, the time savings were measured by the team and converted to money with the company's own cost rate, and the line-balance values were read from the team's chart. Finally, as a single case, the results depend on the product family and the plant, although the same logic can be transferred to other high-mix assembly sections.

6 Conclusions

This study applied the DMAIC cycle to eliminate part-supply errors in the assembly of single-axis linear actuators. The main conclusions are as follows: Pareto stratification showed that 69% of part defects were found at LX assembly and that missing and wrong parts were 76% of them; the FY18 supply-error ratio was 0.31% (about 3,100 DPMO, short-term sigma level about 4.24). A 4M fishbone, on-site verification, and a cause–main cause matrix reduced seven candidate causes to three main causes: kitting several types at once, many receipts and issues of parts, and the absence of a control tool (RQ1). Four countermeasures were selected with a multiplicative scoring matrix (scores 36, 36, 36 and 18) and implemented as one-set kitting, chutes with a two-level conveyor, a central automatic ball feeder serving six tables, relocation of LX parts into the assembly area, and a Navi barcode check (RQ2). Supply errors fell from 6.33 per month to zero in the verification month (exact Poisson test, $p \approx 0.002$), the ball insertion time fell by 1.13 min per cycle, and total labour time fell by about 3,203 h/year (RQ3). The annual saving of US$7,110 for a US$5,200 in-house investment gives a payback time of about 8.8 months and a three-year net saving of about US$16,130. Treating the physical condition of operators, here a pregnant operator, as a design input produced solutions that improved quality, productivity, and ergonomics at the same time.

Future work should extend the monitoring period with a c-chart of supply errors per production volume, quantify the ergonomic load before and after with a standard method, and test whether the Navi check can be connected to the ERP system to cover all product families. The deployment of the central ball feeder to the LX-20 and LX-45 lines will also allow a comparison of results across sizes.

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Competing interests

The authors declare no competing interests.

Author contribution

Conceptualization, Minh Ly Duc (M.L.D.); Do Ngoc Hien (D.N.H); ; methodology, M.L.D.;D.N.H.;N.D.T.;V.T.K.; software, M.L.D.; validation, M.L.D.;D.N.H.; formal analysis, M.L.D.; investigation, M.L.D.; resources, M.L.D..; data curation, M.L.D.;D.N.H.; writing—original draft preparation, M.L.D.;D.N.H.; and; writing—review and editing, M.L.D.;D.N.H.; visualization, M.L.D.;D.N.H.; supervision, D.N.H.; project administration, M.L.D.;D.N.H.;. All authors have read and agreed to the published version of the manuscript.

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