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A Systematic Approach for Raw Material Scraping Control in a Brazilian Metal-Mechanical Industry

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Abstract
This article shows a systematic approach for raw material scrap control in a Brazilian metal-mechanical industry using quality management tools, divided into three stages. First, the scrap reasons were identified using the failure mode and effects analysis. Subsequently, the identified raw material scrap reasons were evaluated and electronically grouped. Lastly, one workflow process and three rework flow actions were developed to minimize raw material scraps. A metal-mechanical industry able to manufacture items for agricultural and automotive parts was explored. A total of 223 raw material scrap reasons were identified, being related to stamping, welding, assembly, and painting processes, grouped into 82 raw material scrap reasons. Before the systematic approach implementation, without grouping raw material scrap reasons, 56% of scraps were categorized as unspecified reasons. After the systematic approach implementation, unspecified reasons decreased to 11.73%, reducing the total cost with unspecified reasons by approximately $55,000.00 in four months.

Keywords
Metal-mechanical industry; Scraping control; Raw material; Quality management tools.

Introduction

Steel is an important raw material for the global economy and the metal-mechanical sector, being used for manufacturing consumer goods, vehicular structures, architectural edifices, electrical and electronic apparatus, machinery, equipment, and tools (Fan & Friedman, 2021; Kim et al., 2022; Nechifor et al., 2020; Francescatto et al., 2023; Júnior et al., 2023). Also, Brazilian industries produced approximately 31,415 thousand metric tons of crude steel in 2020, with an apparent consumption of 21,449 thousand metric tons (World Steel Association, 2021).

Considering the annual steel demand combined with the competitiveness levels required for metal-mechanical industries, the constant production process enhancement is essential to satisfy customer needs while minimizing operational costs (Companys-Pascual et al., 2012; Cañizares & Valero, 2018; Neuenfeldt Júnior et al., 2019; Zaragoza et al., 2019). Particularly, for manufacturing systems within metal-mechanical sectors, the defective items rework and raw material scrap management must be approached to avoid possible lean production losses, specifically process defects (Biswas & Sarker, 2008; Neuenfeldt Júnior et al., 2015; Malinauskienė et al., 2016; Neto et al., 2017; Fortuny-Santos et al., 2021; Francescatto et al., 2023).

The metal-mechanical industry is responsible for manufacturing products for different sectors. In an environment where changes are frequent, managers must outline strategies to improve efficiency, precision, and speed, based on complex manufacturing processes by adopting technological advances and innovations while also having reduced human and material resources available, being a challenge for raw material scrap management (Valiev et al., 2015; Song et al., 2020; Neuenfeldt-Junior et al., 2021a; Fărcean et al., 2024; Neuenfeldt Júnior et al., 2024). Therefore, raw material scrap management based on the main causes of raw material scrap is essential to reduce waste (Khunte, 2018; Javaid et al., 2021).

Considering this research gap, the article shows a systematic approach for raw material scrap control in a Brazilian metal-mechanical industry using quality management tools. The main research

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contributions are: (i) describe how the absence of material resource management can impact the production process; (ii) identify and group the main raw material scrap reasons found in a specific metal-mechanical industry; and (iii) verify the impact of unspecified raw material reasons, given the significant raw material scrap reasons contribution to reduce operational costs.

The remainder of the article is organized as follows. Section 2 describes a literature review focused on quality management tools and raw material scrap in metal-mechanical industries. Section 3 describes the methodology to develop the systematic approach. Section 4 shows the results found with the systematic approach application. Lastly, in Section 5, the conclusion is presented.

Literature review

This section shows articles on metal-mechanical industrial process improvements by applying quality management tools.

Karwasz et al. (2023) used the failure mode, cause-effect analysis, and the five whys method to analyze furniture production process non-conformities, proposing corrective actions. Ly Duc & Bilik (2022) applied the define, measure, analyze, improve, and control (DMAIC) method combined with the plan, do, check, and act (PDCA) cycle to achieve zero material surface defects in the machining center. Herzog & Grabowska (2021) monitored the medical industry quality costs to identify internal and external non-conformities in products and plan improvements at a strategic level. Domínguez-Alfaro et al. (2023) used the brainstorming tool to understand how integral ergo-value stream mapping ergonomic conditions in a metal-mechanical industry can be improved.

Approximately 30% of the steel used in the production process is scrapped by metal-mechanical industries (Flint et al., 2020; Dworak & Fellner, 2021). Fan & Friedman (2021) show that steel scrap has a pivotal role in achieving a sustainable and low-carbon steel industry, since scrap employment in electric arc furnaces constitutes approximately 24% of global steel production, lowering energy consumption and improving decarbonization feasibility through electrification. Holappa (2020) describes the global transitioning trend from fossil fuel utilization to electricity adoption, highlighting steelmaking electrification as a strategy to mitigate CO_2 emissions in response to the projected expansion of steel scrap utilization, from 30% to 50% by 2050.

Hernandez et al. (2018) proposed a comprehensive energy and material utilization analysis within the steel industry, involving extensive resource data and quantifying energy and material savings. Also, a 32.9% sectoral resource utilization efficiency is revealed, with scrap-derived production exhibiting higher efficiency (65.7%) when compared to ore-based production (29.1%). Xylia et al. (2018) show steel scrap availability impacts future steel production and capacity planning. Projections indicate a balanced distribution between primary iron ore-based steel production and secondary scrap-derived production in 2050, resulting in a substantial surge in post-consumer scrap, involving China as the primary exporter with Africa, India, and other Asian nations as importers.

Nechifor et al. (2020) describe the potential to capitalize on obsolete steel scrap availability in the next decades, with a circular and sustainable steel production. Ren et al. (2021) show iron and steel production contributes to 14% of China's CO_2 emissions. To pursue carbon neutrality, augmenting recycled scrap utilization in steel production and limiting emissions from energy sources used in scrap processing are relevant actions. A carbon flow model and an emission factor calculation method were proposed in Zhang et al. (2018), featuring a dual steel mill case study. The variation of specific CO_2 emissions due to material flows and electricity consumption patterns shows that purchased scrap minimizes marked emissions, while self-generated scrap, influenced by production yield, contributes to elevated emissions.

For Oda et al. (2013), increasing the recycling rate, decarbonizing primary steel mills, and decreasing the demand of steel are three paths to reduce CO_2 emissions, as well as recycled scrap usage. In Brazil, cost and carbon emissions reduction through a circular bioeconomy action in the steel industry are described in Souza & Pacca (2021). Also, while steel scrap utilization is regarded as a circular economy strategy, limited domestic scrap availability may prevent carbon emission reduction in steelmaking. Charcoal production emerges as a supplementary alternative for climate change mitigation, offering higher reduction costs as well as fewer uncertainties when compared with scrap utilization. However, economic policies to address supplementary charcoal costs are needed, together with regulations ensuring sustainable charcoal production and the implementation of effective controls within production and logistics systems.

Compared with the literature, the novelty of this article is highlighted by the systematic approach to categorizing unspecified raw material scrap reasons, reducing operational costs in metal-mechanical industries.

Materials & Methods

The systematic approach for raw material scraping control is divided into three stages. First, an item can be incorrectly manufactured due to different failure modes, generating non-conformities during the production process and listed using the failure mode and effect analysis (FMEA) (Kumar & Parameshwaran, 2020; Lamprea et al., 2015; Neto et al., 2017; Yucesan et al., 2021). FMEA is a qualitative reliability analysis method used to evaluate potential failure modes for each item, as well as define each failure effect on sub-items and the overall item function. Thus, the raw material scrap reasons identification (Stage 1) was established based on failure modes verified during the production process.

Subsequently, the identified raw material scrap reasons were evaluated to understand how each scrap reason was integrated within the production process (Boin & Bertram, 2005; Vasileiadis et al., 2023), and electronically grouped (Stage 2), including item code, quantity, occurrence period, operators' identification, and monetary values. The evaluation was conducted by a multidisciplinary team, analyzing all data provided by the failure modes listed using the FMEA.

Lastly, workflow process and rework flow actions were developed to minimize or eliminate raw material scraps (Stage 3) through brainstorming sessions (Chandrasekaran et al., 2019; Kumar & Sosnoski, 2009; Kumar et al., 2009), including participants from the production process, mainly leaders, technicians, and analysts, returning essential insights on how to approach specific failure modes, also identifying if the item should be reworked or discarded. If reworking was feasible, a second brainstorming session was developed to determine strategies to minimize the raw material scrap reasons identified in the production process.

Results

Scenario

The Brazilian metal-mechanical industry approached manufacturing items assembled into agricultural and automotive products. In addition, the production process is divided into sectors, including specific production operations (stamping, welding, painting, and assembly) and technical support (quality, logistics, maintenance, production planning and control, and engineering). Furthermore, robust mechanisms for the identification, control, and management of raw material scrap were not previously utilized within the industry.

Raw material scrap reasons identification

Initially, the FMEA was conducted within the items' families to identify reasons for raw material scrap. The descriptive text field is an open text area where the operators responsible can provide a reason for the scrap. However, the descriptive text fails to standardize the reasons for raw material scrap. Thus, a total of 223 descriptive raw material scrap reasons were identified, being related to stamping, welding, assembly, and painting processes. Considering the production process, the raw material scrap reasons recording was executed by production operators, and the quality sector defined the measures for raw material scrap or rework.

Scrap reasons evaluation and grouping

All 223 descriptive raw material scrap reasons were individually examined by engineering, quality, and production teams using historical quality issues associated with the items' families, removing duplicated scrap reasons and standardizing the words and terminologies, followed by a categorization based on similarities. Tab. 1 shows examples of 15 descriptive raw material scrap reasons grouped into non-specified dimensions, non-specified drilling, non-specified bending, and material surface damage reasons.

Table 1
Examples of four grouped raw material scrap reasons

Descriptive scrap reason	Grouped scrap reason
Assembly problem	Non-specified dimensions
Non-specified dimension	
Unable to mount	
Incorrect bushing position	
Item did not pass the gauge	
Non-specified dimensions	
Non-conforming drilling	Non-specified drilling
Non-compliant drilling	
Non-specified drilling	
Non-specified bending	Non-specified bending
Non-conforming fold	
Incorrect fold	
Plate marks	Material surface damage
Material marks	
Material surface damage	

Next, the 82 grouped raw material scrap reasons were categorized by production processes (general, stamping, assembling, painting, welding, and logistics), as shown in Tab. 2.

Considering the main grouped raw material scrap reasons based on proportional monetary impact per year (Fig. 1), 38% were related to scheduling and logistics failure modes and 61% to quality failure modes, being the most grouped raw material scrap reasons found in the stamping process, as well as logistical transportation, material quality, or by raw material oxidation.

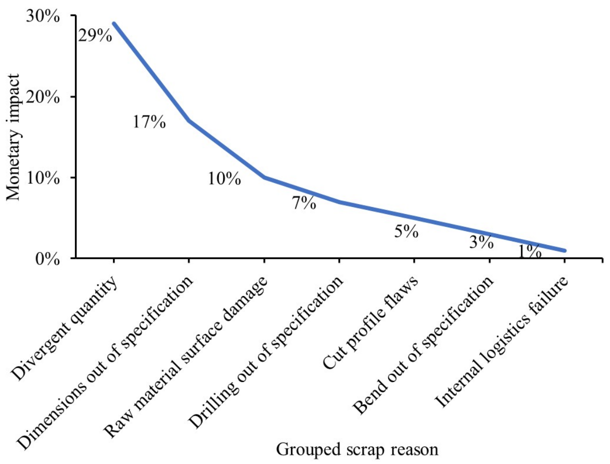

Fig. 1. Main grouped raw material scrap reasons

The grouped raw material scrap reasons were obtained by failure modes verified within the production process, such as an item manufactured with discrepancies in dimensions, drilling, or welding. Programming errors, lost items, or damaged packing scrap reasons are classified as scheduling and logistics failure modes. In specific, quality raw material scrap reasons are associated with the stamping (encompassing unwinding, laser cutting, plasma cutting, shearing, pressing, and machining operations), welding, assembly, and painting processes.

Considering the stamping process, the unwinding operation represents the initial production process phase, composed of the steel coils cut into sheets with precise lengths required for the subsequent laser cutting process. The main raw material scrap reasons found for the unwinding operation were: (i) Surface material damage involving marks, scratches, or material deformation, originating from the process or the material itself; and (ii) warped sheet, describing material deformation and flatness irregularity.

For the laser cutting, plasma cutting, and shearing operations, the main failure modes were: (i) Drilling deviation from specifications, where the dimensions

Table 2
Grouped scrap reasons by production process

Production process	**Grouped scrap reasons**	
General	Without a specific reason	Non-specified beating
	Superficial material damage	Incorrect component
	Lack of operation	Higher dimension
	Oxidation	Lower dimension
	Excess oil or grease	Maintenance test
	Incorrect packing	Test item
	Leaking	Component break
	Damage material	
Stamping	Non-specified dimensions	Out-of-position drilling
	Non-specified drilling	Reading error
	Non-specified folding	Nozzle collision
	Cut profile flaws	Warped sheet
	Incorrect tagging	Out of square steel
	Burrs presence	Warped item
	Incorrect lamination direction	Off-center nozzle
	Obstructed drilling	Serrated cut
	Bias fold	Lack of material
	Wrong side fold	Lack of drilling
	Material crack	
Assembling	Lack of assembly components	Unbalanced material
	Incorrect assembly	
Painting	Wrong color	Lack of coverage
	Expired painting	Paint in a paint-free region
	Non-specified roughness	Non-specified layer
	Compromised painting's visual appearance	Non-specified brightness
	Detachment	Damaged in heat treatment
	Ink bleed	Non-specified painting

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Production process	**Grouped scrap reasons**	
Welding	Presence of contaminants	Welding bite
	Inadequate process parameter	Solder leakage
	Deformation at the weld point	Weld crater
	Excessive Weld Penetration	Lack of weld filler
	Weld porosity	Lack of weld fusion
	Weld glazing	Excessive gap
	Presence of weld spatter	Replaced the welded component
	Non-specified weld	Out-of-dimension weld
	Solder sag	Turned welded component
	Macrograph	
Logistic	Internal logistics failure	Logistical delay
	Incorrect identification	Detour
	FIFO failures	Items not found
	Mixed material	Production order adjustment
	Deviating quantity	Programming error
	Damaged package	No demand item

do not align with the specified design; (ii) flawed cut profile, resulting in a serrated cut; (iii) nozzle collision, due to the cutting nozzle colliding with the cut items or any sheet warping region; (iv) off-centered nozzle and reading error, signifying the nozzle misalignment with the axis centerline and inaccurate readings; and (v) inadequate process parameters, emerging when current, gas, pressure, or cutting speed differs from the specified range.

Subsequently, material-forming operations through hydraulic, eccentric, and bending presses are conducted. Within presses, operations including cutting, bending, and material shaping are performed, while in bending machines, only the bending operation is performed. The primary failure modes identified are: (i) Bending deviation from specifications, when the item's bend line or dimension does not align with requirements; and (ii) Material cracking, due to inadequate process parameters and material properties. Additionally, machining can be used to obtain items with specific forms, dimensions, and surface finishes. The failure modes resulting in machining scrap are related to cut profile flaws, drilling deviation from specifications, and inadequate process parameters.

The primary failure modes considering welding operations are welding deviation from specifications due to process anomalies leading to non-conformities, contamination when consumables or surfaces are tainted by moisture, sweat, oils, or dirt, and inadequate process parameters. During the assembly operation, the main failure mode is the incorrect assembly with mismatched components, which impacts the original item's functionality. Lastly, for the e-coat, liquid, or powder painting process, failure modes are associated with improper parameter setups and contaminants during the painting operation, which impacts surface protection and item finishing.

Furthermore, additional raw material scrap reasons are identified in the production process including dimensions deviating from specifications (items with dimensions not aligning with design specifications), damaged material (items sustain damage during processing or handling), oxidation presence (rust formation), and warped item (material deformation relative to flatness).

To monitor and operationalize the grouped raw material scrap reasons, an information recording is conducted using the system analysis program (SAP) software, extensively employed in key business domains including procurement, production, material management, sales, marketing, finance, and human resources, guiding all grouped raw material scrap reasons documentation during the production process.

Workflow process and rework flow actions

A workflow was developed to deal with the grouped raw material scrap reasons and to aid the information recording, as shown in Fig. 2. Initially when a nonconformance is detected, the item must be identified within the production process. The quality sector is activated, initiating a technical analysis to solve the issue and determining whether the item can be reworked, based on a favorable cost-benefit ratio. If the rework is feasible, the item is not scrapped, generating a rework production order and reintroducing the item into the production process. However, when rework is not feasible, the recording and subsequent physical scrapping procedure is conducted.

Scrapping is accomplished by marking the scrap directly on the production order or through SAP. During the item manufacturing, the scrap is added to the production order, within the respective workstation, together with the corresponding reason. When

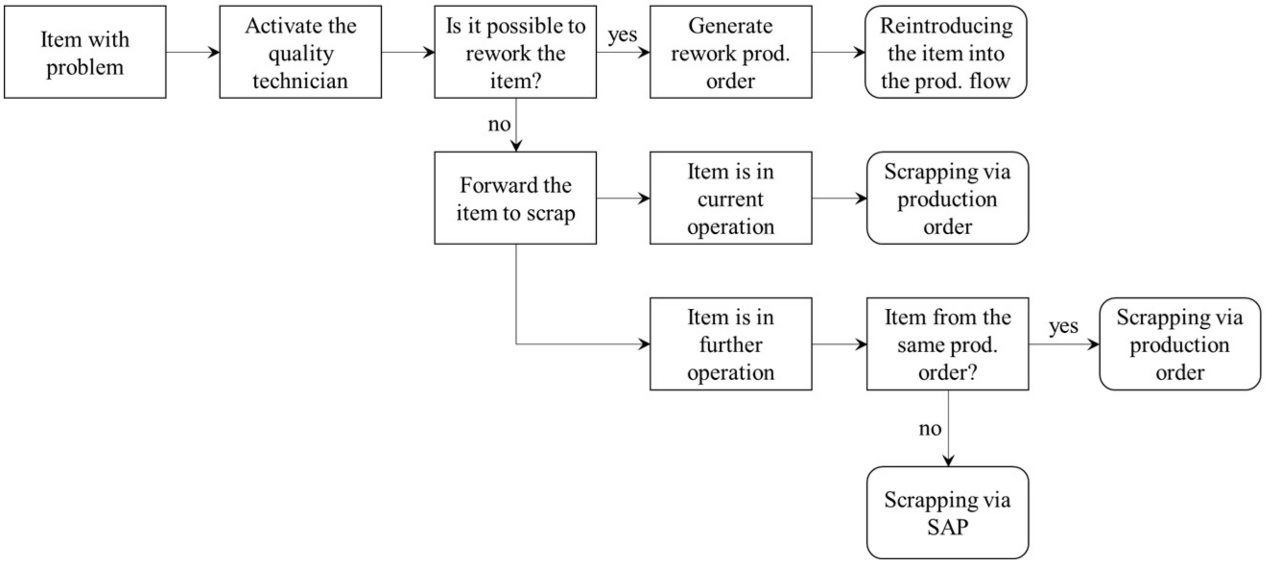

Fig. 2. Grouped raw material scrap reason workflow

a non-conformity is detected and the item is in the subsequent operation or already stored, two scenarios are verified: (i) If the item remains within the same production order and progresses to a subsequent operation, the scrap entry should be registered on the production order; and (ii) if the item is stored or continues to the subsequent operation within another production order, scrapping should be conducted via SAP, where is necessary to verify the scrap origin by finding the responsible production operation or technical support area.

With the grouped raw material scrap reasons and the technical area being activated when a non-conformity occurrence is found, rework actions can be implemented for items where scrapping can be avoided.

Rework workflows were formulated for non-specified dimensions deviation, material surface damage, and non-specified drilling. Specifically, from non-specified dimensions deviation issues (Fig. 3), if rework is feasible, a rework production order is generated. Subsequently, the quality sector evaluates the item to define

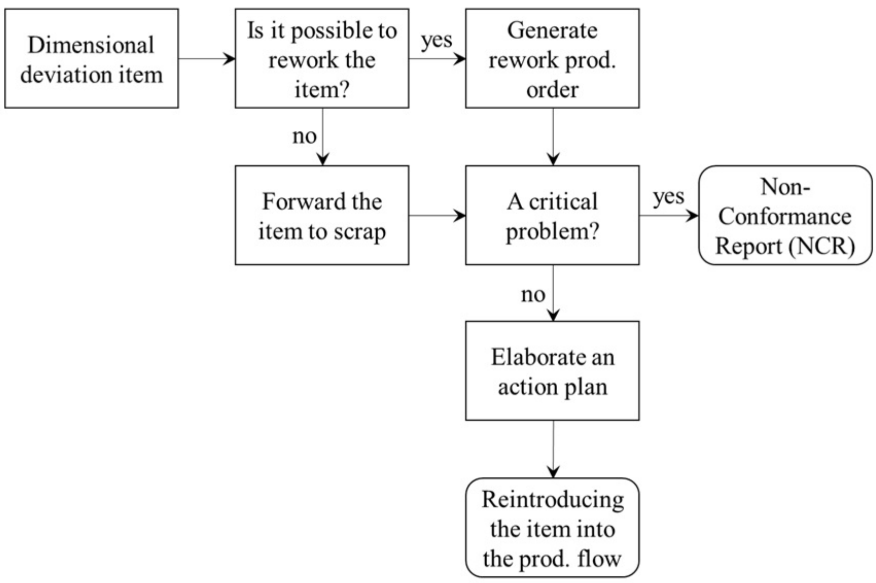

Fig. 3. Rework flow actions for non-specified dimensions deviation

the issue severity level. For a problem to be considered critical, the following aspects are considered: (i) Problem recurrence; (ii) significant quantity of scrapped items; (iii) production stoppage occurrence; and (iv) high scrap value (exceeding US$ 20.31). Therefore, if any critical aspects are identified, a Non-Conformance Report (NCR) is developed, facilitating an in-depth analysis of the factors that led to scrapping. However, an action plan to rectify the failure must be elaborated.

When reworking is feasible, a rework production order is generated, considering the material surface damage (Fig. 4), with the item being reintroduced into the production process. If reworking is unfeasible, a physical item examination by the quality sector is conducted to find the surface marks' origin, specifically when scratches or dents stem from tooling issues or are inherent to the raw material. Subsequently, a secondary analysis to define if the problem qualifies as critical is developed, consequently creating an NCR or corrective action plan. To classify the problem as critical, the subsequent aspects are required: (i) Whether the item is visible, adhering to the designated drawing class; (ii) quantity of scrapped items; (iii) whether raw material damages prevent the attainment of specifications outlined in standards; and (iv) if the raw material deviates from the established quality standard defined with the supplier.

For non-specified drilling issues (Fig. 5), the drilling source (laser cutting, plasma cutting, press operations, or machining) is investigated, followed by the feasibility analysis related to the item rework, with a framework similar to the rework flow for non-specified dimensions deviation issues (Fig. 3), including the critical problem definition.

Before the systematic approach implementation, quality sector activations were not demanded. The operator or leader would assess the issue and determine whether rework or scrap was required. From the systematic approach implementation, the quality sector is activated to analyze all incidents, defining if rework or scrap is necessary. Additionally, rework production orders were not consistently generated. Rework was categorized as either simple or complex, and a rework production order was only requested for complex rework, hampering the rework registration within the SAP system, which is mandatory after the systematic approach implementation for all rework incidents.

Quantitative implementation results

Approximately $125,000.00 in total scrap value between January and April 2022 was verified before the systematic approach implementation, with 56% of scrap categorized as unspecified reason. After the systematic approach implementation, due to grouping raw material scrap reasons, between September and December 2022, the unspecified reasons decreased to 11.73%, as shown in Tab. 3.

Due to the previous absence of identified reasons for raw material waste, after grouping, apart from

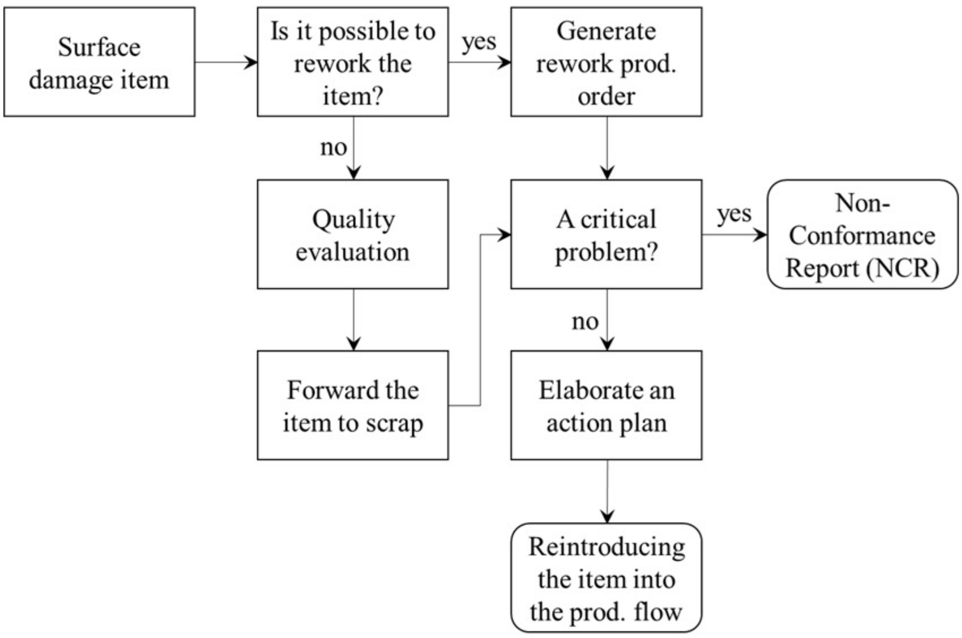

Fig. 4. Rework flow actions for non-specified drilling

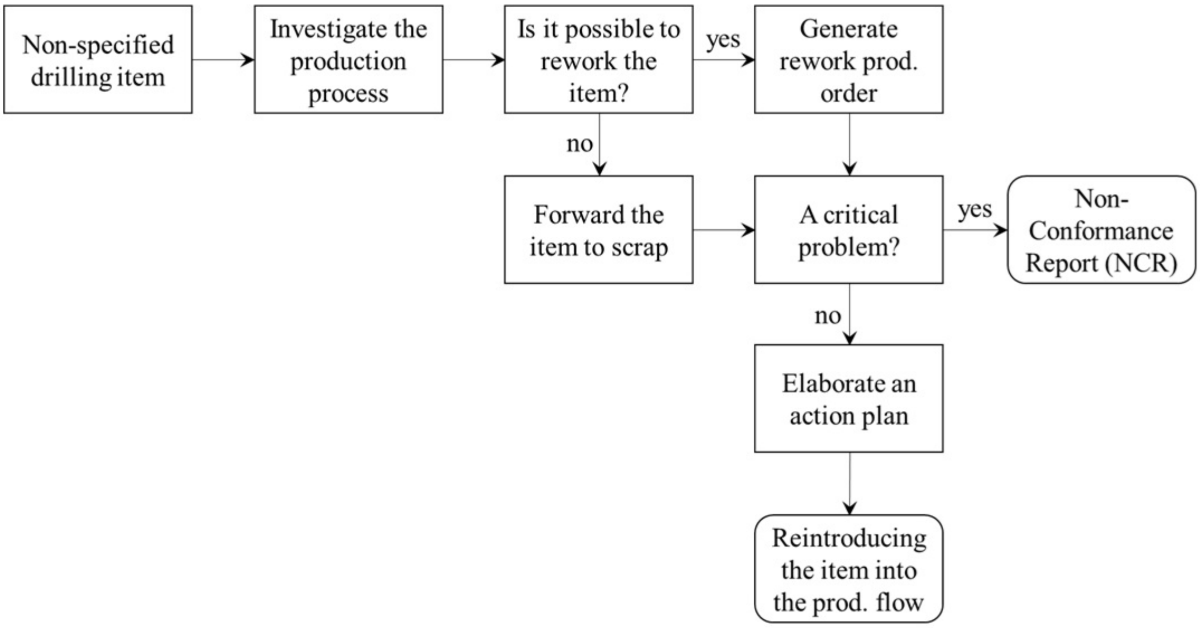

Fig. 5. Rework flow actions for non-specified drilling

Table 3
Comparative before and after the systematic approach implementation

Classification	Before	After
Unspecified reason	55.67%	11.33%
Deviating quantity	15.33%	25.16%
Non-specified dimensions	11.98%	21.29%
Material surface damage	7.94%	15.29%
Non-specified drilling	2.36%	6.26%
Cut profile flaws	2.36%	1.36%
Non-specified bend	1.57%	5.57%
Internal logistics failure	1.49%	8.85%
Warped sheet	0.86%	0.55%
Damaged material	0.73%	4.33%

the unspecified reason, the reasons increased, which was directly related to the visualization of the reasons in the production system, not being possible before the systematic approach implementation. In addition, to mitigate the financial impact of the three main raw material scrap reasons (deviating quantity, non-specified dimensions, and material surface damage), rework workflows were developed to guide future analyses and interventions.

Conclusion

The systematic approach proposed is useful for reducing natural resource utilization by controlling the reasons for raw material scrap during the production process, constraining the scrap registration possibility and avoiding unspecified reasons. For the Brazilian metal-mechanical industry studied, the systematic approach enhanced the identification of raw material scrap reasons, reducing by 44% the reasons classified as unspecified.

The correct identification of raw material scrap reasons contributes to reducing operational costs, allowing the improvement of profit margins with products sold. As an example, the raw material scrap reasons records can be employed to improve the decision-making regarding future production process investments to reduce operational costs.

A well-defined system for dealing with raw material scrap is useful for establishing standardized procedures and promoting effective collaboration between different sectors. However, the implementation of continuous improvements is not feasible in the absence of a solid industrial structure.

Finally, future research can be conducted to develop novel industrial material resource management tools, specifically for raw material waste obtained during the production process.

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