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Improving financial and environmental performance through MFCA: A SME case study

Aditya Kumar Sahu [a], [*], R.K. Padhy [a], Debabrata Das [b], Amitosh Gautam [c]

[a] Indian Institute of Management, Kashipur, Uttarakhand, 244713, India
[b] National Institute of Industrial Engineering, Powai, Mumbai, 400087, India
[c] National Productivity Council, Gandhinagar, Gujrat, 382028, India

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ABSTRACT

SMEs around the globe are often challenged by the issues related to productivity enhancement, material usage, waste management and sustainability. Material flow cost accounting (MFCA) is considered as a green productivity tool that can be utilised by SMEs to overcome these challenges. Despite the benefits, its adoption among SMEs, especially in developing countries, remains low. The purpose of this research is to examine how MFCA can be suitably implemented in an SME set-up to improve the financial and environmental performance of the enterprise. This study utilises case based research methodology to exemplify the application of MFCA tool in an Indian steel pipes and tubes manufacturing SME. As a part of MFCA analysis, material cost, system cost and energy cost at each quantity center was calculated to identify inefficiencies in the production process of the SME. Thereafter, several solutions were implemented to address these inefficiencies. The result of the MFCA implementation showed an overall annual savings of 21,028,452 INR (USD 302,350) through an investment of 495,400 INR (USD 7123). The present study reveals that the application of MFCA tool leads to higher productivity, better energy efficiency and improved environmental performance. The SME's performance was also monitored for five years to study the long-term benefits of MFCA implementation. The findings suggest that, post MFCA implementation, the return on invested capital of the SME increased by 29.37% and the material usage cost reduced by 26.58%. This research would be beneficial to managers, practitioners, and policymakers for effectively implementing MFCA in SMEs.

1. Introduction

According to a recent report, worldwide consumption of raw materials will be doubled by 2060 due to expansion in the global economy and rise in living standards (OECD, 2018). This, as a result, will intensify the waste generated during the manufacturing of products compared to today. Small and medium scale enterprises (SMEs) around the globe significantly contribute to the economy (Revell et al., 2010). They contribute to around 90 percent of the businesses around the world, responsible for 60–70% of employment and up to 50% of the gross domestic product (GDP) of the countries (UN, 2018). However, they are also significant contributors to environmental contamination. Compared to large scale industries, SMEs generally do not efficiently manage their waste (Van Hoof and Lyon, 2013). Their share in overall industrial waste generation is estimated to be about 70% (Caldera et al., 2019). Additionally, their energy consumption is around 74 Exajoules (EJ) which is above 13% of total energy demand globally (De et al., 2018). Although industrialization is vital for the economic growth of the country, one cannot ignore its negative environmental impacts. Further, stringent government policies and increased pressure from society due to deteriorating climatic conditions force manufacturers to develop their manufacturing practices by taking the environmental concerns into account (Luthra and Mangla, 2018). The increasing competitive pressure has impelled SME manufacturers to align their business process for achieving sustainability. This, as a result, has stimulated both researchers and SME managers to devise different management tools and frameworks for establishing sustainable manufacturing practices.

Several environmental management tools and policy

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[*] Corresponding author.
E-mail addresses: aditya.fpm2016@iimkashipur.ac.in (A.K. Sahu), rk.padhy@iimkashipur.ac.in (R.K. Padhy), debabrataiitb@gmail.com (D. Das), amitoshg@gmail.com (A. Gautam).

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frameworks have been adopted in the past, like cleaner production methodology, lifecycle costing and ISO 14000 (environmental management) but only a few of these consider environmental and financial performance holistically. Moreover, most of these environmental management tools have been developed keeping the large-scale enterprises in mind. Hence these tools, when applied to small scale enterprises, fail to incorporate all elements of the tool due to scarcity of financial resources, man-power, awareness, knowledge, and expertise (Johnson and Schaltegger, 2016). In such scenario, the Material Flow Cost Accounting (MFCA) tool can be beneficial for SMEs as it is developed to enhance both environmental and financial performance of the enterprise (Schaltegger and Zvezdov, 2015). According to ISO 14051: (2011), MFCA is defined as a “tool for quantifying the flows and stocks of materials in the manufacturing process or production lines in both physical and monetary units”. In other words, MFCA can be described as a management accounting tool that enables enterprise to effectively manage the use of both material and energy by improving the existing practices. MFCA works on the concept of ‘quantity center (QC)’. At each QC, the inputs and waste are quantified in physical and monetary terms (Christ and Burritt, 2015). The quantity of input and waste generated is first determined in physical terms and then the associated monetary costs are allocated at each QC. The Japanese Ministry of Economy, Trade and Industry (METI) has referred QCs as “theoretical units of MFCA calculation” (METI, 2011). The MFCA tool focuses on quantifying both the marketable products (referred to as “positive products”) and the process wastes (referred to as “negative products”) produced during the manufacturing operations (Zhou et al., 2017). This quantification enables to trace the flow of materials going into soil, water or air which can further assist in environmental assessment (Guenther et al., 2015).

Implementation mechanisms and effectiveness of productivity improvement tools vary across nations due to cultural factors, economic conditions, and government policies (Christ and Burritt, 2016). The awareness as well adoption level of MFCA among SMEs in Germany and Japan is considerably high as both these countries were the prime contributors towards the initial development of MFCA tool (Zhou et al., 2017). MFCA has been widely promoted by METI in Japan from the year 2000, i.e. since a decade before it became ISO 14051: 2011 standard (Nakajima et al., 2015). As of today, more than 300 SMEs in Japan have implemented MFCA, out of which some enterprises have even extended it to the supply chain level (METI, 2011; Prox, 2015). Realising the benefits of MFCA implementation in Germany and Japan, enterprises in China has also started its implementation across several industrial parks (viz. Chinese Huangxing). On the contrary, in India, the implementation of MFCA in SMEs is significantly low compared to those in Japan, Germany and China (Guenther et al., 2015).

India is an emerging and fast-growing economy. In India, SMEs contribute around eight percent of the total GDP through production, export and employment generation (GOIMSME, 2016). The implementation of MFCA tool in India is still in the preliminary stage as majority of the SMEs lack awareness about its financial and environmental benefits. Moreover, unlike enterprises in advanced economies, SMEs in India lack data-driven/evidence-based decision making (Mathur et al., 2012). Most of SMEs in India are family owned businesses, and perform operations based on the traditional business methods due to availability of cheap labour (Panizzolo et al., 2012). Indian SMEs primarily focus on their production output, and generally do not pay much attention towards managing production waste due to less stringent environment norms (Seth et al., 2018). In addition to their reluctance to bear the costs associated with the implementation of MFCA, Indian SMEs also insist on knowing whether the tool had previously been implemented in some similar enterprises nearby. Besides, they do not foresee the additional financial benefits of adopting MFCA tool in their enterprise. Therefore, academic evidence which exhibits environmental and financial benefits of MFCA tool in a different cultural setting will provide an important source of motivation for SME managers to implement it in their enterprise (Christ and Burritt, 2016).

In recent years, with the launch of “Make in India” initiative, there has been substantial growth in manufacturing sector in India (Seth et al., 2018). The “Make in India” programme, started in 2014, supports SMEs with an aim to make India the world’s largest manufacturing hub (Centobelli et al., 2019). However, along with economic growth, the rapid industrialization will invariably lead to increased resource depletion, waste generation and environmental degradation. Hence, it is important for SMEs in India to manufacture products in a sustainable manner. In the present study, we respond to this need, and focus on effective implementation of MFCA (a green productivity tool) in an Indian manufacturing SME. Moreover, to the best of our knowledge, real-life case studies of Indian SMEs explaining systematically derived MFCA-results are rare and missing. In this context, our study also addresses the call by Christ and Burritt (2015) that emphasized the need to focus on the research related to MFCA implementation in developing nations.

The objective of this study is to apply the MFCA tool in an Indian SME engaged in steel pipes and tubes manufacturing. The performance of the enterprise has been monitored for five years to examine the financial and environmental impact of MFCA implementation. The study shows a detailed successful MFCA implementation with highly promising results in terms of cost and material savings. This study also shows that how implementation of MFCA will make the enterprise environmentally conscious and economically viable. It is envisioned that the case study findings of present research will inspire other SMEs in developing nations to implement MFCA. Subsequently, the present case study will help in spreading awareness and promoting the implementation of MFCA in Indian SMEs. The remaining article has been divided as follows: Section 2 describes the concept of MFCA tool and the relevant literature associated with it. The research methodology is discussed in Section 3. An explanatory case study is presented in Section 4. Section 5 highlights the results and discussions. Finally, the article ends with conclusions stating the implications, limitations and future research directions of the present study in section 6.

2. Material flow cost accounting (MFCA)

MFCA was developed in Augsburg, Germany in the late 1990s as a green productivity management tool (Wagner, 2015). It is a diagnostic tool that helps in productivity enhancement through the reduction in use of material, energy, and human resources. MFCA enables the enterprise to visualize the material flows in the production process. The material flow analysis is done through the QCs. In MFCA, the QCs dissect a complete manufacturing system into fragments. The QCs trace the flow and inventory of materials through the concept of ‘mass balance’ (Wagner, 2015). As per the mass balance concept, the total weight of the positive and negative products should always be equal to that of the input. MFCA primarily focus on the waste (e.g. energy loss, material scrap, unutilised human resource potential and so forth) produced during the manufacturing operations. The cost allocations into positive and negative products at each QC are classified as follows:

i) Material costs (includes raw material purchase cost and selling cost of scrap).
ii) Energy costs (includes electricity and fuel purchase cost).

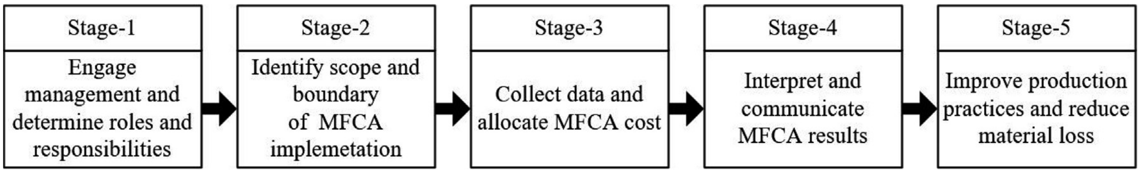

Fig. 1. Guidelines for MFCA implementation.

iii) System costs (includes labor cost, depreciation cost, transportation cost, and maintenance cost).
iv) Waste disposal cost (includes cost of handling the waste).

Hence, the cost of waste is more accurately identified in MFCA compared to traditional cost accounting (Fakoya and van der Poll, 2013). MFCA also enables the enterprise to produce the same amount of finished products with a lesser amount of input (Kasemset et al., 2015). By implementing MFCA, an enterprise can analyse its internal process efficiency as MFCA accounts for material, energy, system and waste disposal cost in a single tool. MFCA can be either applied in a single enterprise or an entire supply chain regardless of size, activity or location (Schmidt, 2015). Fig. 1 shows the guidelines for MFCA implementation as per the ISO 14051: (2011) framework. These guidelines have been further elaborated in the methodology section of this article.

For identifying the relevant MFCA literature, the keyword phrase “material flow cost accounting” was searched in the Scopus database. Total 63 peer-reviewed journal articles were identified in the MFCA literature published till August 2019 in the English language. A total of 55 articles focusing mainly on MFCA was sorted through manual screening based on the availability of full texts. After the screening, it was found that most of the articles were focused on the issue of cleaner production and waste management. It was also observed that the “Journal of Cleaner Production” published the highest amount of academic literature related to MFCA.

In this study, MFCA literature is categorized into conceptual and applied research in order to understand the research trends. Conceptual research consists of theoretical development, expansion, frameworks and the literature review articles related to MFCA, whereas applied research consists of the application of MFCA in various SMEs and large scale enterprises. Majority of the applied research are present in the form of case studies in the existing literature. A summary of conceptual and applied research have been presented in Table 1. As per the analysis, out of 55 articles, 29 (52.73%) articles contribute to conceptual based research and 26 (47.27%) articles are based on action and applied research. Recent articles published in both of these fields suggest further growth and development in MFCA related research. The existing MFCA related literature has laid more emphasis on conceptual based research compared to applied research (Christ and Burritt, 2015). The applied or action-based research is vital for understanding the implementation of MFCA in practice. Guenther et al. (2015) suggest that the possible reason for the low academic publications of applied research is due to the enterprise confidentiality policies. The enterprises are hesitant to share detailed achievements of their MFCA implementation because of fear and competition.

Table 2 summarizes the MFCA-related case studies by grouping them based on the information like authors, application area, country and methodology for understanding the applicability of the tool in different contexts. In all of the case studies, the implementation of MFCA showed substantial benefits in terms of cost saving with an additional reduction in waste generation. The extended MFCA techniques have also been proposed by scholars that can be used as future environmental management accounting tools (Christ and Burritt, 2015). Recent case studies shown in Table 1 reflect the application of both standard and extended MFCA in the enterprises. For example, Dunuwila et al. (2018a) applied MFCA along with a life cycle analysis (LCA) to establish environmental and financial sustainability practices in the rubber manufacturing enterprise. Dunuwila et al. (2018b) further integrated MFCA with pareto analysis, what-if analysis, cost-benefit analysis along with LCA for improving the environmental and financial sustainability. Yagi and Kokubu (2018) identified the important characteristics of material flow management and proposed an analytical framework to expand the use of MFCA. Zhou et al. (2017) implemented a modified version of MFCA to achieve the 3R (Reduce, Recycle and Reuse) principles of circular economy in a Chinese steel industry enterprise. Bierer et al. (2015) proposed an extended approach by integrating MFCA with life cycle costing and LCA approach to enhance the applicability of MFCA. Chompu-Inwai et al. (2015) proposed a combined MFCA and design of experiments approach to reduce defects and environmental impact in a Thailand wood manufacturing SME. Fakoya and van der Poll (2013) also proposed an extended framework by integrating MFCA with ERP. The methodology of implementing MFCA is continually expanding to increase the potential and applicability of the MFCA tool. A new ISO 14052: 2017 framework has been established which provides guidelines for implementing MFCA in a supply chain level. The ISO 14052: 2017 is based on ISO 14051: 2011 MFCA general framework and incorporates principles such as commitment, trust, collaboration and shared benefit that are vital for successful MFCA implementation in a supply chain. Recent

Table 1
Identified streams of MFCA research.

Type of research	Related publications
Conceptual research	Bierer et al. (2015); Bautista-Lazo and Short (2013); Burritt et al. (2019); Christ and Burritt (2017, 2015); Dierkes and Siepelmeyer (2019); Doorasamy (2015, 2016); Jasch (2006, 2015); Kokubu and Kitada (2015); Kouřilová and Sedláček (2014); Kurdve et al. (2015); Marota et al. (2017); Mbedzi et al. (2018); Nakajima et al. (2015); Nakano and Hirao (2011); Nyide (2016); Pauliuk (2018); Rieckhof et al. (2015); Schmidt (2015); Schaltegger and Zvezdov (2015); Schmidt and Nakajima (2013); Sulong et al. (2015); Wagner (2015); Wang (2015); Yagi and Kokubu (2018, 2019); Zhao (2012)
Applied or action or research	Behnami et al. (2019); Chompu-Inwai et al. (2015); Debnath (2014); Dunuwila et al. (2018a, 2018b); Dekamin and Barmaki (2019); Cagno et al. (2012); Fakoya (2015); Fakoya and van der Poll (2013); Huang et al. (2019); Hyrslová et al. (2011); Jakrawatana et al. (2016); Kasemset et al. (2015); Kasemset and Boonmee (2015); Li et al. (2019); Mahmoudi et al. (2017); Papaspyropoulos et al. (2012); Rieckhof and Guenther (2018); Schmidt et al. (2015); Takakuwa et al. (2014); Thanki and Thakkar (2016); Wan et al. (2015); Wan and Ng (2015); Wang et al. (2017); Zhou et al. (2017); Zou et al. (2019)

Table 2
Summary of MFCA related case-study research.

Authors (year)	Application area	Country	Methodology used
Zou et al. (2019)	Aluminum production	China	MFCA with life cycle theory
Behnami et al. (2019)	Petrochemical wastewater treatment plant	Iran	MFCA with data reconciliation technique
Li et al. (2019)	Paper manufacturing	China	MFCA with resource value flow analysis
Huang et al. (2019)	Flat glass panel manufacturing	Japan	MFCA
Dekamin and Barmaki (2019)	Soybean production	Iran	MFCA
Rieckhof and Guenther (2018)	Wood processing	Germany	MFCA with life cycle assessment (LCA)
Dunuwila et al. (2018a)	Crepe rubber production	Sri Lanka	MFCA with LCA
Dunuwila et al. (2018b)	Crepe rubber production	Sri Lanka	MFCA with LCA, Pareto, what-if and cost benefit analysis
Wang et al. (2017)	Printed circuit board (PCB) manufacturing	Taiwan	MFCA
Zhou et al. (2017)	Iron and steel production	China	MFCA with the 3R (reduce, reuse and recycle) concept of circular economy
Mahmoudi et al. (2017)	Oil refinery wastewater treatment plant	Iran	MFCA
Jakrawatana et al. (2016)	Starch and ethanol production	Thailand	MFCA
Thanki and Thakkar (2016)	Cylinders manufacturing	India	MFCA with value stream mapping and pinch analysis
Chompu-Inwai et al. (2015)	Wood products manufacturing	Thailand	MFCA with design of experiments
Fakoya (2015)	Micro-brewery enterprise	South Africa	MFCA
Wan et al. (2015)	Aluminum production and sago starch extraction process (two case studies)	Malaysia	Mathematical algorithm for MFCA implementation
Kasemset et al. (2015)	Textile manufacturing	Thailand	MFCA
Schmidt et al. (2015)	Aluminum parts production	Germany	MFCA
Wan and Ng (2015)	Sago starch and wastewater treatment plant	Malaysia	MFCA
Kasemset and Boonmee (2015)	Meatball production	Thailand	MFCA
Takakuwa et al. (2014)	Precision component manufacturing	Japan	MFCA
Debnath (2014)	Food processing unit	India	MFCA with greenhouse gas accounting
Fakoya and van der Poll (2013)	Brewery enterprise	South Africa	MFCA with the integration of ERP
Papaspyropoulos et al. (2012)	Non-profit forestry organization	Greece	MFCA
Cagno et al. (2012)	Electro-mechanical items manufacturing	Italy	MFCA with general activity based environmental costing
Hyrslová et al. (2011)	Ceramic tile manufacturing	Czech Republic	MFCA

literature (see Higashida, 2020; Nakajima et al., 2015) claims that application of MFCA at supply chain level helps in further reducing the cost and the environmental impact. However, the implementation needs to be first initiated at the enterprise level.

3. Methodology

This study employs case-based research methodology. Case study provides an empirical enquiry that establishes a causal link by answering the ‘what’ and ‘how’ questions of the given research (Yin, 2017). Swamidass (1991) stated that field-based research helps to reduce the gap in practical applicability of the academic research. It captures and studies the actual phenomenon of the field through dialogue and observation. Therefore, case study method is ideal to understand the MFCA implementation process and its impact on financial and environmental performance of the enterprise. The steps of MFCA implementation process has been illustrated in Fig. 2. These steps are based on the principles of ISO 14051:2011 framework which focuses on the input materials and process waste for increasing cost and environmental efficiency. As per ISO 14051: 2011 standard, the MFCA implementation involves following five stages: Stage 1- engage management and determine roles and responsibilities, Stage 2- identify scope and boundary of MFCA implementation, Stage 3- data collection and MFCA cost allocation, Stage 4- interpret and communicate MFCA results, and Stage 5- improve production practices and reduce material loss. These five stages are in the form of various clauses under ISO 14051: 2011 standard with are further divided according to plan-do-check-act cycle. The stage 1 (clause 6.2 and 6.3) and stage 2 (clause 6.4 and 6.5) both represents the *plan* phase, stage 3 (clause 6.6, 6.7 and 6.8) represents the *do* phase, stage 4 (clause 6.9 and 6.10) represents the *check* phase and stage 5 (clause 6.11) represents the *act* phase.

The enterprise selected for this study agreed to provide a consent letter to the researchers for conducting the research. Both qualitative and quantitative data was collected for the case study. The qualitative data was obtained through semi-structured interviews with the team members involved in MFCA implementation. The quantitative data was obtained through the documents and materials such as presentation slides, charts, reports, ISO 14051: 2011 manual, and financial sheets prepared during the MFCA implementation and analysis. In addition to this, several observations were also made during site visits. Data of five years (from the financial year 2011–2016) that covers the period of both before and after MFCA implementation was collected to examine the impact and sustainable benefits associated with MFCA tool. The impact on the enterprise’s financial performance was measured through return on invested capital (ROIC) and the yearly material cost.

4. Case study: implementation of MFCA in an Indian SME

The case study was conducted in steel pipes and tubes manufacturing enterprise situated in the western part of India having nearly 250 employees. The enterprise manufactures variety of pipes and tubes made of cold drawn carbon and alloy steel. Some of the product categories are - seamless straight tubes and pipes, ‘u’-bend, bright-annealed, fuel injection and hydraulic cylinder tubes. The MFCA was implemented by the enterprise with the aim

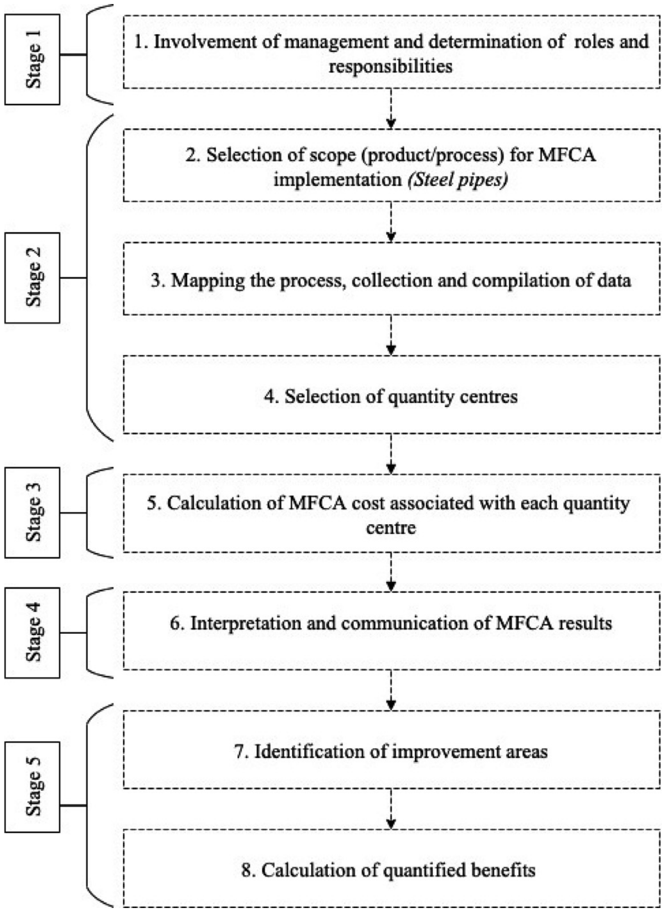

Fig. 2. MFCA implementation steps.

to achieve the financial and environmental performance benefits. It was decided by the enterprise's management to implement the MFCA tool from the financial year 2012. The MFCA implementation steps illustrated in Fig. 2 was deployed in the selected enterprise. The complete process of MFCA implementation, documentation and the study took nearly two years. The implementation steps are described below in detail:

4.1. Involvement of management and determination of roles and responsibilities

When the MFCA tool was introduced to the enterprise, the need was felt by the management to apply it in their manufacturing unit. The management accepted its implementation to gain further insights into their production process for continual improvement. The implementation team was assigned various roles and responsibilities for obtaining necessary resources, monitoring progress, reviewing results and collaborating effectively between different departments within the enterprise.

4.2. Selection of the scope (product/process) for MFCA implementation

The next step is to define the scope of MFCA implementation by identifying the target product/process. The target process for MFCA implementation in this study was restricted to the '*precision steel tubes*' manufacturing facility. This unit was chosen due to the high demand for precision steel tubes.

4.3. Mapping the process, collection and compilation of the data

Fig. 3 represents the flow of order fulfillment process based on the customer product specifications. The operations start with picking up the raw material followed by the activities of lubrication, pointing, cold drawing, heat treatment, straightening, cutting, deburring, U-bending, hydro testing, dipping in oil, inspection, marking, packing and finally the delivery of the precision tubes. Upon discussion with the top management, these activities were mapped in the form of eleven sub-processes by the MFCA implementation team to collaborate, maintain records and track the flow of information. After mapping the process, the period of one month was specified for data collection to perform the MFCA analysis. This duration was chosen for minimizing the effect of any significant variation in the manufacturing process that can affect the usability and reliability of data. The eleven sub-processes are described below:

4.3.1. Raw material stockyard

The enterprise used steel tubes (known as mother tubes) as the primary input raw materials. These tubes were procured from vendors located in China through bulk ordering. These tubes come with a variable wall thickness (0.4 mm–0.12 mm), eccentricity and length. On arrival, the tubes were stored in the raw material stockyard. Based on the product to be manufactured, decisions on selecting the desired length and thickness of the tubes are made.

4.3.2. Lubrication

This stage involves lubricating the tube surface with a variety of chemical solutions. The mother tubes are submerged in acidic baths to remove foreign particles (such as dust and rust). This was done to improve the surface finish of the tubes.

4.3.3. Pointing

In this step, the outer diameter of the tube was reduced by the desired amount by pulling the tube through the pointing die.

4.3.4. Cold drawing

The tubes were cold drawn to reduce its overall cross-section. This process was accomplished by passing the mother tubes through a cold drawing die which reduces the diameter and increases the tube length. The die was mounted on a draw bench, which consists of a long table, a die stand containing the mould and a carriage that was used to grip and draw the tube. The next step was the oil drawing process in which bundles of tubes were dipped into an oil tank.

4.3.5. Heat treatment

This process was used to alter the microstructure of the tube (physical and chemical properties) for providing surface hardness, temperature resistance, ductility and strength.

4.3.6. Straightening

The tubes may get slightly bent after the drawing and heat treatment process. Hence, the tubes were passed through straightening machines which have a series of vertical and horizontal rollers in mutually perpendicular planes to ensure straightening.

4.3.7. Cutting and deburring

The cutting and deburring process was used to remove the front pointed portion of the straightened tube. This process involves both manual labor and a cutting machine for the removal of the unwanted part.

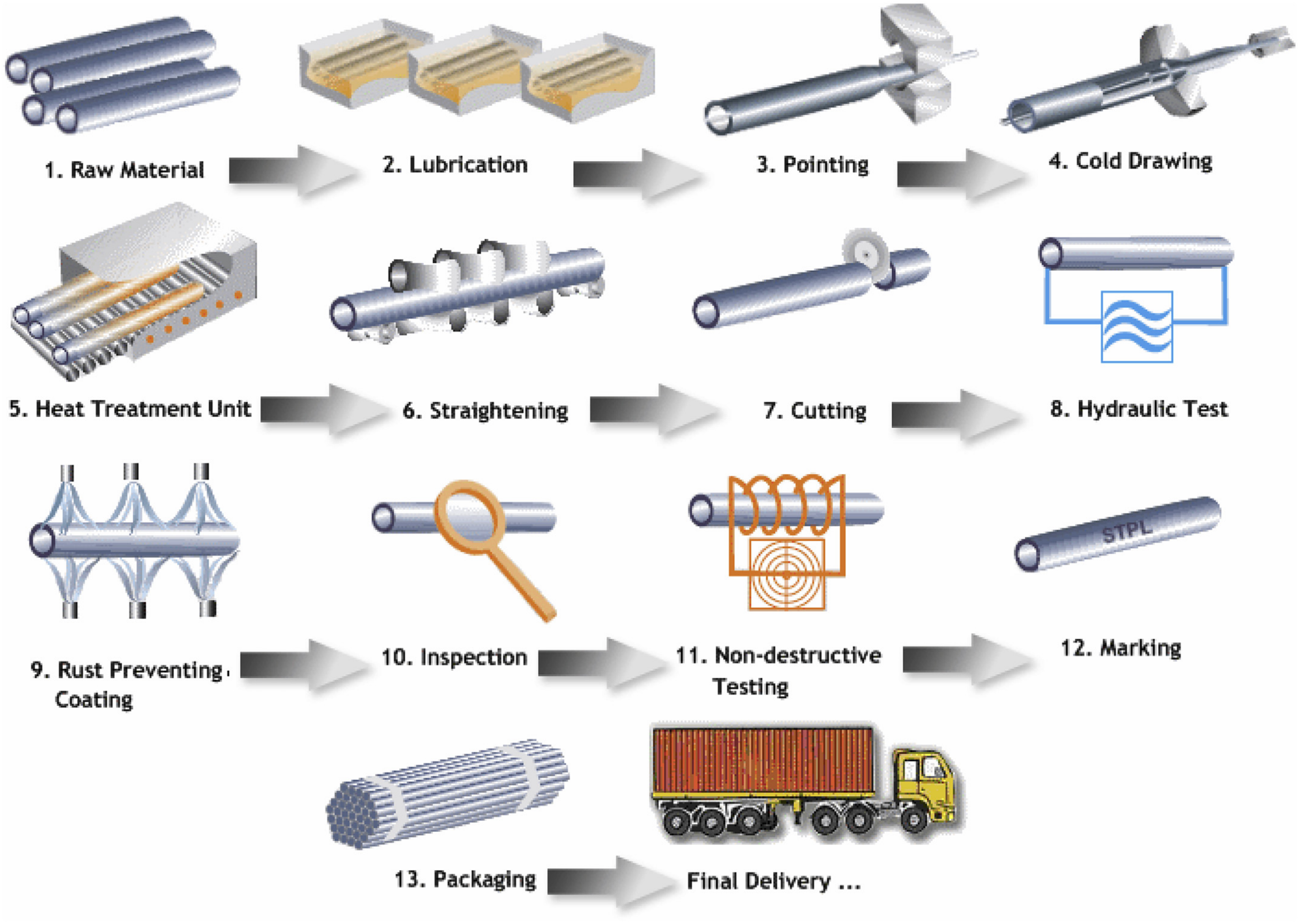

Fig. 3. Order fulfillment process and the material flow model.

4.3.8. *Hydro test*

The hydro test was performed on the tubes to check for the leakages.

4.3.9. *Rust prevention coating*

The processed tubes were dipped in an oil bath to provide the rust prevention coating. An overhanging crane was used for handling the tubes in this process.

4.3.10. *Inspection, testing and marking*

In this step, visual inspection and testing of the tubes was done through sampling. Thereafter, the marking of the tubes was done for easy identification. The marking procedure involved manual screen-printing of the product specifications over the tube surface.

4.3.11. *Packing and delivery*

The processed precision steel tubes were wrapped in plastic sheets and placed in wooden boxes before shipping it to the customers. This was done to prevent the tubes from damage/scratches.

4.4. *Selection of QCs*

The level of details required, and the complexity involved in MFCA analysis depend on the selection of QCs. A QC can be an individual sub-process or a combination of consecutive sub-processes. The QCs are selected based on several factors such as nature of enterprise activities, number of products manufactured, plant layout, size of enterprise, technical considerations of the production process, and material flow details of individual sub-process in terms of cost and weight. Table 3 provides a summary of the material flow details of various sub-processes of the case study SME. It gives information related to the *number of raw materials added in each sub-process, cost of the current raw materials added in each sub-process*, *cost of the consecutive waste generated in each sub-process*, *weight of current input raw materials* and *weight of consecutive waste*. By considering all the above factors and capturing the knowledge and experience of the SME staff members acquainted with the production processes, total six QCs were formed to implement MFCA in the SME. Table 4 summarizes the list of QCs.[1] Manufacturing sub-process 1 (i.e. raw material stockyard) is considered as a separate QC because of comparatively higher cost and weight of input raw materials (refer Table 3) than other sub-processes. The raw materials (i.e. mother tubes) were received from various Chinese suppliers in different quantity and variety. Hence, separate quantification of inputs and waste generated at this sub-process would help the SME managers to track supplier

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[1] The same number of QCs are also obtained using an integer programming approach (refer Appendix A in the supplementary file for the detailed algorithm). However, this algorithm would be more apt for a large-scale enterprise having more complex production structure.

Table 3
Material flow details at individual manufacturing sub-process.

Sub-process number	Manufacturing sub-process	Number of input raw materials (Quantity)	Cost of current input raw materials (INR)	Cost of consecutive waste (INR)	Weight of current input raw materials (Kg.)	Weight of consecutive waste (Kg.)
1	Raw material stockyard	1	23,003,736	956,040	371,028	15,420
2	Lubrication	5	2,660,036	2,553,957	98,532	94,591
3	Pointing	2	124,000	124,000	880	880
4	Cold drawing	2	349,500	337,860	1400	1380
5	Heat treatment	3	285,478	299,924	6818	7051
6	Straightening	0	0	0	0	0
7	Cutting and deburring	2	145,284	389,254	741	4676
8	Hydro test	3	139,442.45	159,887.45	1417.88	1836.23
9	Rust prevention coating	2	556,968	529,248	7697	7312
10	Inspection, testing and marking	3	43,527	576,501	900	9708
11	Packing and delivery	8	981,384.35	6805	5015.05	82

Table 4
Quantity centers.

Quantity center (QC)	Sub-process number	Manufacturing sub-process at each quantity center
QC 1	1	Raw material stockyard
QC 2	2	Lubrication
QC 3	3,4,5,6	Pointing, cold drawing, heat treatment, and straightening
QC 4	7,8,9	Cutting, deburring, hydro test and rust prevention coating
QC 5	10	Inspection, testing and marking
QC 6	11	Packing and delivery

performances in terms of number of defective items. Manufacturing sub-process 2 (i.e. lubrication) is also treated as a separate QC because of comparatively higher cost and weight of consecutive waste than other sub-processes. Moreover, the disposal of waste in lubrication sub-process involves treatment of a variety of hazardous chemical solutions. Therefore, environmental concern is another reason to treat sub-process 2 as a separate QC. Manufacturing sub-process 3, 4, 5, and 6 (i.e. pointing, cold drawing, heat treatment and straightening) are combined to form QC 3. The existing plant layout was a major reason behind combining these sub-processes (since the manufacturing equipment required in the four sub-processes were in very close proximity to one another). Manufacturing sub-process 7, 8, and 9 (i.e. cutting & deburring, hydro test and rust prevention coating) are combined to form QC 4. Like the previous QC, existing plant layout was a major reason to combine these three sub-processes. Manufacturing sub-process 10 (i.e. inspection, testing and marking) is treated as a separate QC mainly because it involves quality control process. Also, the cost and weight of waste generated in this sub-process are third-highest (refer Table 3) among all the 11 sub-process. The last manufacturing sub-process (i.e. sub-process 11 - packing and delivery) is also treated as a separate QC since the packaging and delivery of finished goods are done at a different facility away from the manufacturing area (to have better interaction with the customers related to product delivery). Additionally, the number of input raw materials is highest, and the cost of current input raw materials in this sub-process is third-highest among all the 11 sub-process.

4.5. *Calculation of MFCA cost associated with each QC*

In this step, the input costs and the cost of waste at each QC were calculated. The mass balancing concept was utilised to determine the cost of positive and negative products. The positive product of the previous QC goes as the input of the subsequent QC along with other additional inputs required in that QC. The positive and negative material costs at each QC are calculated and shown in Table 5. Other costs such as energy costs (EC) and system costs (SC) are assigned into positive and negative costs based on the proportion of the positive and negative material cost (MC) (Kasemset et al., 2015). The MFCA cost allocation is illustrated in Fig. 4.

4.6. *Interpretation and communication of MFCA results*

The results of the MFCA analysis are interpreted to discover QCs that contribute to significant financial loss and environmental impact (in terms of waste). From the MFCA material balance (refer Table 5), it can be observed that maximum material loss is occurring at the QC 2. The cost of negative product is 2,553,957 INR[2] (USD 36,721) i.e. 10.34% with reference to the material input. The cost of the negative product with reference to the material input at other QCs are as follows: 956,040 INR (4.16%) at QC 1; 761,784 INR (3.32%) at QC 3; 1,078,389.45 INR (4.69%) at QC 4; 576,501 INR (2.63%) at QC 5; and 6805 INR (0.03%) at QC 6. The maximum amount of financial loss aggregating the material, energy and system loss is also observed at the QC 2 (refer Fig. 4). The total negative product cost aggregating the material, energy and system loss at QC2 is 2,600,437.28 INR (USD 37,389). The summary of the positive and negative costs in terms of material cost, energy cost, system costs and waste management cost have been presented in Table 6. Waste management cost (WC) was not considered in the analysis as the process of waste management was outsourced. The percentage-wise positive and negative cost allocations in MFCA is also illustrated in Fig. 5. Fig. 5 suggests that more focus should be given to reduce material loss as it accounts for the highest percentage of negative product cost (20.98%) under MFCA. After analysis, the results of MFCA were communicated to relevant stakeholders in order to reduce the financial and environmental loss.

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[2] INR – Indian Rupee. (1 USD = 69.55 INR).

Table 5
MFCA material balance. INR- Indian National Rupees.

Data period	(1 month)
Type of product	Steel tube

No.	Input	Quantity (Kg)	Material Cost (INR)
1	Packed steel pipes and tubes: 62 INR/kg	371,028	23,003,736
	Total (A)	**371,028**	**23,003,736**

Quantity Center 1
Name of process: Raw material stock yard

Material loss			
No.	**Type of Material loss**	**Quantity (Kg)**	**Material Cost (INR)**
1	Material waste (steel strips, tubes etc): 62 INR/kg	15,420	956,040
	Total (B)	**15,420**	**956,040**

Negative product %	4.16%
Positive product %	95.84%

No.	Input	Quantity (Kg)	Material Cost (INR)
1	**Previous process positive product (A-B)**	355,608	22,047,696
2	HCL: 25 INR/kg	93,723	2,343,075
3	Metcot 220: 65 INR/kg	2,860	185,900
4	Steric acid: 69 INR/kg	1,663	114,747
5	Metcot 210: 82 INR/kg	120	9,840
6	Caustic: 39 INR/kg	166	6,474
	Total (C)	**454,140**	**24,707,732**

Quantity Center 2
Name of process: Lubrication

Material loss			
No.	**Material loss**	**Quantity (Kg)**	**Material Cost (INR)**
1	Waste acid (chemical sludge): 27 INR/kg	94,591	2,553,957
	Total (D)	**94,591**	**2,553,957**

Negative product %	10.34%
Positive product %	89.66%

No.	Input	Quantity (Kg)	Material Cost (INR)
1	**Previous process positive product (C-D)**	359,549	22,153,775
2	Pointing die: 150 INR/kg	80	12,000
3	Grippers: 140 INR/kg	800	112,000
4	Cold drawing die: 80 INR/kg	150	12,000
5	Drawing oil: 270 INR/kg	1,250	337,500
6	Ammonia: 41 INR/kg	6,533	267,853
7	Descaling chemical: 95 INR/kg	60	5,700
8	MS-wire: 53 INR/kg	225	11,925
	Total (E)	**368,647**	**22,912,753**

Quantity Center 3
Name of processes: (a) Pointing, (b) Cold drawing, (c) Heat treatment and (d) Straightening

Material loss			
No.	**Material loss**	**Quantity (Kg)**	**Material Cost (INR)**
1	Rejected tubes: 62 INR/kg	135	8,370
2	Sample tubes taken out for quality check: 62 INR/kg	128	7,936
3	Used Pointing die: 150 INR/kg	80	12,000
4	Used grippers: 140 INR/kg	800	112,000
5	Used cold drawing die: 80 INR/kg	150	12,000
6	Used Drawing oil: 270 INR/kg	1,200	324,000
7	Used ammonia: 41 INR/kg	6,533	267,853
8	Used descaling chemical: 95 INR/kg	60	5,700
9	Used MS-wire: 53 INR/kg	225	11,925
	Total (F)	**9,311**	**761,784**

Negative product %	3.32%
Positive product %	96.68%

No.	Input	Quantity (Kg)	Material Cost (INR)
1	**Previous process positive product (E-F)**	359336	22,150,969
2	Abrasive cutter: 133 INR/kg	704	93,632
3	Deburring tool: 1396 INR/kg	37	51,652
4	Jigs tool: 45 INR/kg	495	22,275
5	Rubber seals: 780 INR/kg	7.65	5,967
6	Hydralic oil: 121.50 INR/kg	915.23	111,200.45
7	Pressure gauge: 1000 INR/kg	3	3,000
8	Rust preventing oil: 72 INR/kg	7694	553,968
	Total (G)	**369,191.88**	**22,992,663.45**

Quantity Center 4
Name of processes: (a) Cutting, deburring, (b) Hydro test and (c) Rust prevention coating

Material loss			
No.	**Material loss**	**Quantity (Kg)**	**Material Cost (INR)**
1	Rejected tubes: 62 INR/kg	2,206	136,772
2	Pointed end cuts of tube: 62 INR/kg	2,155	133,610
3	Used abrasive cutter: 133 INR/kg	704	93,632
4	Used deburring tool: 1396 INR/kg	37	51,652
5	Used jigs tool: 45 INR/kg	495	22,275
6	Used hydralic oil: 121.50 INR/kg	915.23	111,200.45
7	Used pressure gauge: 1000 INR/kg	3	3,000
8	Ued rust preventing oil: 72 INR/kg	7,309	526,248
	Total (H)	**13,824.23**	**1,078,389.45**

Negative product %	4.69%
Positive product %	95.31%

No.	Input	Quantity (Kg)	Material Cost (INR)
1	**Previous process positive product (G-H)**	355,367.65	21,914,274
2	Cotton material: 27 INR/kg	831	22,437
3	Marking slate: 327.50 INR/kg	2	655
4	Marking chemical: 305 INR/kg	67	20,435
	Total (I)	**356,267.65**	**21,957,801**

Quantity Center 5
Name of process: Inspection, testing and marking

Material loss			
No.	**Material loss**	**Quantity (Kg)**	**Material Cost (INR)**
1	Rejected tubes: 62 INR/kg	8,862	549,444
2	Cotton material: 27 INR/kg	831	22,437
3	Marking slate: 327.50 INR/kg	2	655
4	Marking chemical: 305 INR/kg	13	3,965
	Total (J)	**9,708**	**576,501**

Negative product %	2.63%
Positive product %	97.37%

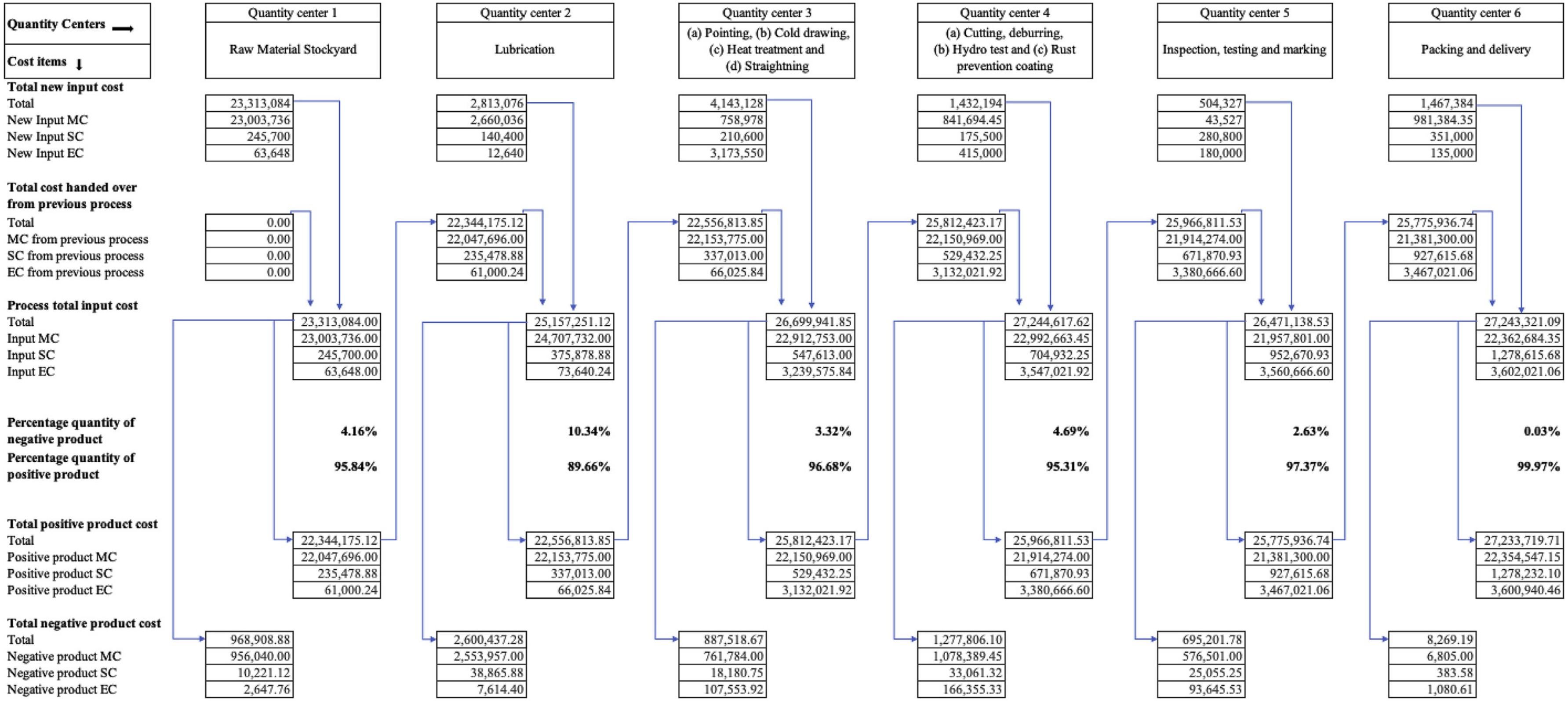
No.	Input	Quantity (Kg)	Material Cost (INR)
1	**Previous process positive product (I-J)**	346,559.65	21,381,300
2	Wooden box: 291.45 INR/kg	2,550	743,197.50
3	Hession cloth: 130 INR/kg	463	60,190
4	HDPE: 60 INR/kg	698	41,880
5	Plastic sheets: 99 INR/kg	496	49,104
6	Steel strips: 95 INR/kg	614	58,330
7	Packing clip: 56 INR/kg	18	1,008
8	End caps: 120 INR/kg	154	18,480
9	Adhesive tape: 417 INR/kg	22.05	9,194.85
	Total (K)	**351,574.70**	**22,362,684.35**

Quantity Center 6
Name of process: Packing and dispatch

Material loss			
No.	**Material loss**	**Quantity (Kg)**	**Material Cost (INR)**
1	HDPE: 60 INR/kg	31	1,860
2	Plastic sheets: 99 INR/kg	25	2,475
3	Steel strips: 95 INR/kg	26	2,470
	Total (L)	**82**	**6,805**

Negative product %	0.03%
Positive product %	99.97%

INR- Indian National Rupees



Quantity Centers → / Cost items ↓	Quantity center 1: Raw Material Stockyard	Quantity center 2: Lubrication	Quantity center 3: (a) Pointing, (b) Cold drawing, (c) Heat treatment and (d) Straightning	Quantity center 4: (a) Cutting, deburring, (b) Hydro test and (c) Rust prevention coating	Quantity center 5: Inspection, testing and marking	Quantity center 6: Packing and delivery
Total new input cost						
Total	23,313,084	2,813,076	4,143,128	1,432,194	504,327	1,467,384
New Input MC	23,003,736	2,660,036	758,978	841,694.45	43,527	981,384.35
New Input SC	245,700	140,400	210,600	175,500	280,800	351,000
New Input EC	63,648	12,640	3,173,550	415,000	180,000	135,000
Total cost handed over from previous process						
Total	0.00	22,344,175.12	22,556,813.85	25,812,423.17	25,966,811.53	25,775,936.74
MC from previous process	0.00	22,047,696.00	22,153,775.00	22,150,969.00	21,914,274.00	21,381,300.00
SC from previous process	0.00	235,478.88	337,013.00	529,432.25	671,870.93	927,615.68
EC from previous process	0.00	61,000.24	66,025.84	3,132,021.92	3,380,666.60	3,467,021.06
Process total input cost						
Total	23,313,084.00	25,157,251.12	26,699,941.85	27,244,617.62	26,471,138.53	27,243,321.09
Input MC	23,003,736.00	24,707,732.00	22,912,753.00	22,992,663.45	21,957,801.00	22,362,684.35
Input SC	245,700.00	375,878.88	547,613.00	704,932.25	952,670.93	1,278,615.68
Input EC	63,648.00	73,640.24	3,239,575.84	3,547,021.92	3,560,666.60	3,602,021.06
Percentage quantity of negative product	**4.16%**	**10.34%**	**3.32%**	**4.69%**	**2.63%**	**0.03%**
Percentage quantity of positive product	**95.84%**	**89.66%**	**96.68%**	**95.31%**	**97.37%**	**99.97%**
Total positive product cost						
Total	22,344,175.12	22,556,813.85	25,812,423.17	25,966,811.53	25,775,936.74	27,233,719.71
Positive product MC	22,047,696.00	22,153,775.00	22,150,969.00	21,914,274.00	21,381,300.00	22,354,547.15
Positive product SC	235,478.88	337,013.00	529,432.25	671,870.93	927,615.68	1,278,232.10
Positive product EC	61,000.24	66,025.84	3,132,021.92	3,380,666.60	3,467,021.06	3,600,940.46
Total negative product cost						
Total	968,908.88	2,600,437.28	887,518.67	1,277,806.10	695,201.78	8,269.19
Negative product MC	956,040.00	2,553,957.00	761,784.00	1,078,389.45	576,501.00	6,805.00
Negative product SC	10,221.12	38,865.88	18,180.75	33,061.32	25,055.25	383.58
Negative product EC	2,647.76	7,614.40	107,553.92	166,355.33	93,645.53	1,080.61

MC = material cost (in INR), SC = system cost (in INR), EC = Energy cost (in INR)

Fig. 4. MFCA cost calculations.

Table 6
Summary of the positive and negative costs in MFCA.

	Material cost (INR)	System cost (INR)	Energy cost (INR)	Waste management cost (INR)	Total cost (INR)
Positive Product	22,354,547.15 (79.02 %)	1,278,232.10 (91.04%)	3,600,940.46 (90.48%)	(–)	27,233,719.71 (80.88%)
Negative product (loss)	5,933,476.45 (20.98%)	125,767.90 (8.96%)	378,897.55 (9.52%)	(–)	6,438,141.90 (19.12%)
Total	28,288,023.60 (100%)	1,404,000 (100%)	3,979,838.01 (100%)	(–)	33,671,861.61 (100%)

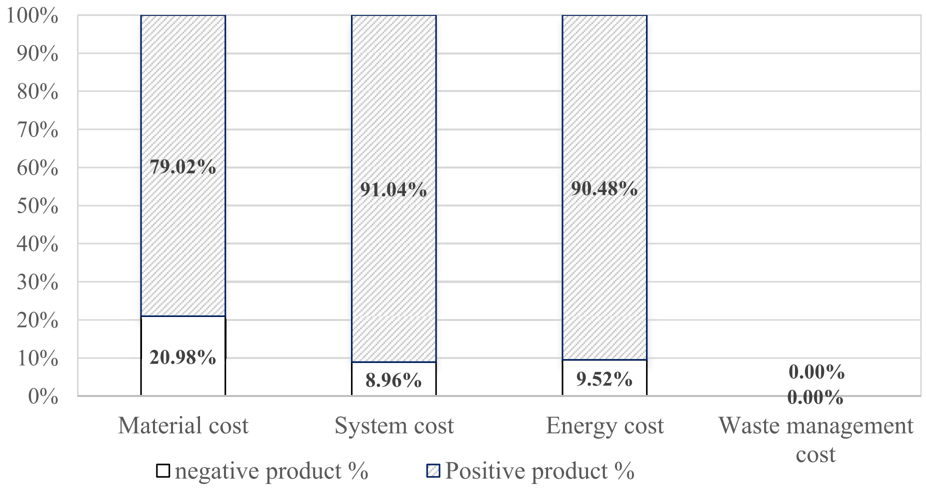


Fig. 5. The MFCA cost allocation (positive vs. negative).

4.7. *Identification of improvement areas*

In this step, the material flows were analysed in detail to identify the inefficient resources (material, energy and human resources). Improvement areas were identified by tracing the materials going into the product, water, soil or air. This tracing of material flow in physical and monetary terms helps the enterprise to perform both financial and environmental assessment simultaneously (Guenther et al., 2015). The QCs generating losses have been identified on the basis of MFCA cost calculation. The implementation team brainstormed on the improvement areas and evaluated them based on the practicality, implementation cost and estimated benefits. Prioritization rule was set to identify improvement areas in the production process. The focus on reducing the material loss was given first priority as it accounted for the highest negative product cost compared to the cost of energy and system loss (refer Table 6). Thereafter, the QC having higher negative product cost compared to others was given more preference. If the QC has more than one sub-process then the sub-process having higher material loss in terms of cost within the QC was given more priority for improvement compared to other merged sub-processes. For example, the QC 2 was given first priority for improvement as it accounts for the highest negative product cost (2,553,957 INR) followed by QC 4 (1,078,389.45 INR), QC 1 (956,040 INR) and so forth. In case of QC 4, rust prevention coating (529,248 INR) was given more priority followed by cutting and deburring (389,254 INR), and hydro test (159,887.45 INR) for identifying the improvements possibilities within the QC (refer Table 3). The material flows, present waste management practices and identified improvement areas have been discussed below in detail.

4.7.1. *QC 1: Raw material stockyard*

The material loss generated in the form of defective metal tubes and steel strips were sold to institutional scrap dealers. In this QC, the mother tubes were visually inspected for abnormalities.

The variable length and the wall thickness of mother tubes often created difficulty in terms of the selection of raw material batches as the scrap generated in the form of end cuttings depends on the length of the batch selected.

4.7.2. *QC 2: Lubrication*

This process (lubrication) is a metal pickling process in which the chemical solution removes the rust and dust by forming a thin layer of solution over the tube surface. The material loss is in the form of chemical sludge. In this process, out of total 98,532 kg acid; 4% (i.e. 3941 kg) sticks onto the surface of the mother tubes, 2% (i.e. 1971 kg) gets evaporated, and the rest 94% (i.e. 92,620 kg) gets contaminated during the acid bath. Both the contaminated and evaporated acid (92,620 + 1971 = 94,591 kg) are treated as process waste/material loss. The waste (i.e. chemical sludge – also known as spent pickle liquor) is hazardous in nature. Hence, it is sent directly to a common effluent treatment facility located nearby for further treatment. Thereafter, it is finally discarded as per the environmental protection laws.

The main issue in this sub-process was the frequent acid bath changeover. The raw material tubes were submerged directly into an acid bath which caused frequent acid changeover. Moreover, the lubrication process was not regulated by any standard operating procedure. The process was solely dependent on the visual inspection of the handling personnel as no measuring instruments were installed to check the quality parameters of the pickling and lubrication facility. By cleaning a lot of tubes at once, there were chances that some tubes would remain unclean. Also, no temperature indicators and control gauges were installed for operational control. This created problems in the next process in the form of reworking or rejection of the tubes.

4.7.3. QC 3: Pointing, cold drawing, heat treatment and straightening

As per the current waste management practices, rejected tubes, sample tubes taken out for quality check, used pointing dies, used grippers, used cold drawing dies and used MS wires were sold to the scrap dealer. Out of total 1250 kg drawing oil, 4% (i.e. 50 kg) sticks onto the surface of the tubes, 2% (i.e. 25 kg) spills on the ground, and the rest 94% (i.e. 1175 kg) gets contaminated during the operation. Both the contaminated and spilled oil (1175 + 25 = 1200 kg) are treated as process waste/material loss. The contaminated drawing oil is discarded and sold to outside vendors which they recycle. In this QC, ammonia is used to maintain the furnace atmosphere so that the metal pipes are protected from oxidation during the high-temperature heat treatment process. Similarly, de-scaling chemical is added during the heat treatment process to maintain the surface finish of tubes and protect them from scale formation over the tube surface. Since all the ammonia (6533 kg) and de-scaling chemical (60 kg) get mixed with the products of combustion, these are considered as material loss in Table 5. The Straightening process does not generate any waste. In this QC, following improvement areas were identified:

4.7.4. Pointing

The pointed length that had to be cut off was eight inches per tube which later became scrap for the unit. This generated process scrap could be reduced by reducing the pointing length of the tube.

4.7.5. Cold drawing

The drawing bench machine used to run in an unloaded condition (a resource waste). Also, the next process had to remain idle until the excess oil was drained out in the oil drawing process. The production was affected due to the waiting period and more oil was wasted in some cases due to urgency. At times the floor became slippery due to improper design which increased the chance of accidents.

4.7.6. Heat treatment

Material loading at the furnace was not properly planned. To keep the furnace running continuously, most of the times it was operated in an under loaded condition. This practice of underutilizing the furnace capacity led to wastage of precious resource like PNG (Piped Natural Gas) in the form of exhaust gases. The manpower required for unloading annealed tubes was high. Since the process was manual, six men were employed for unloading the tubes. Also, frequent breakdowns occurred in the heat treatment process. The total breakdown at the furnace was approximately 100 hr per month. The tubes used to get overheated due to the improper design of the cooling zone. The furnace was also under loaded to overcome the overheating problem. This resulted in wastage of energy leading to less production output. Moreover, the waste heat from the furnace in terms of exhaust gases was let out directly into the atmosphere at around 250 °C. This could have been utilised for heating purposes instead.

4.7.7. QC 4: Cutting, deburring, hydro test, and rust prevention coating

The waste generated in the form of rejected tubes, point end cuts (metal pieces), discarded abrasive cutter, used deburring tool, used jig tools, and faulty pressure gauges were sold to the scrap dealer. The hydraulic oil is changed as per the maintenance schedule adopted by the unit due to the reason that the oil loses its viscosity over time. The quantity of hydraulic oil that was replaced is shown as material loss since it was completely discarded and cannot be reused. The rust prevention oil gets contaminated due to direct dipping of tubes and loses its efficacy over time. Out of total 7694 kg of rust preventing oil, 5% (i.e. 385 kg) sticks onto the surface of the tubes, 1% (i.e. 77 kg) spills on the ground, and the rest 94% (i.e. 7232 kg) gets contaminated during the operation. Both the contaminated and spilled oil (7232 + 77 = 7309 kg) are treated as process waste/material loss. The contaminated oil is sold to the oil dealers which they recycle. In this QC, following improvement areas were identified:

4.7.8. Cutting and deburring

In this process, the abrasive cutting machine used to run in an unloaded condition. Also, the process scrap generated in the form of end cuts was high due to improper gripping of cutting machine.

4.7.9. Rust prevention coating

In this sub-process, the operator had to wait until excess oil was drained out of tubes for the next inspection process to take place. The production was affected due to the waiting period. Many times, in order to meet the production timelines, a huge quantity of oil was wasted as very less time was provided for the oil to rinse out of the tubes. This also made the shop-floor slippery and accident-prone.

4.7.10. QC 5: Inspection, testing and marking

The wastes generated in this QC are rejected tubes, rejected marking slate, lost marking chemical, and used cotton material. The inspection and quality check department discards the tubes which do not conform to the standard specifications. Hence, they were sold as scrap to the scrap dealer. During marking process of the tubes, 54 kg of the marking chemical sticks to the tubes' surface. The rest (i.e. 13 kg) of the chemical either sticks on to the surface of the marking slate or spills on the ground during the operations, and is hence treated as a material loss. All the marking slates are discarded after use. The cotton cloth material is used for cleaning the tube surfaces for marking the tube identification and batch codes. The same cotton cloth material is then used to clean the ground where this marking chemical is spilled. The whole cotton cloth material, post usage, is discarded as industrial waste and sent to the secure landfill sites.

Earlier, in the marking process, a new marking slate was used for each new batch of the finished product, i.e. the marketing slate was discarded after a single-batch use. However, as per the suggestion of the MFCA implementation team, it was decided to reuse these slates two to three times.

4.7.11. QC 6: Packing and delivery

The wastes generated in this QC are HDPE, plastic sheets, and steel strips. The steel strips are used to bundle the finished products during packing. It is also used to grip the wooden boxes to prevent the tubes from damage/scratches during transportation. During the bundling and gripping process, out of total 614 kg of steel strips, 4.24% (i.e. 26 kg) gets damaged. The damaged steel strips are treated as waste and sold to the scrap dealer. HDPE is used to wrap the bundled finished products. Improper handling often resulted in tearing of HDPE. During the wrapping process, out of total 698 kg of HDPE, 4.44% (i.e. 31 kg) got torn. The HDPE wrapped finished products are kept inside wooden boxes. Thereafter, plastic sheets are used to wrap the wooden box. During the wrapping process, out of total 496 kg of plastic sheets, 5.04% (i.e. 25 kg) got torn. The torn HDPE and plastic sheets are treated as waste and sent to secure landfill sites.

Earlier, the wooden boxes used for packaging were 1-inch thick and fully covered (see Fig. 6). However, the MFCA implementation team suggested that wooden boxes could be redesigned to reduce the usage of wood resulting in material and cost saving.

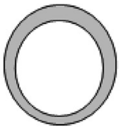
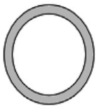
Before MFCA implementation	After MFCA implementation
The wall thickness eccentricity of mother tube used was 0.4 mm. 	The wall thickness eccentricity was reduced to 0.15 mm. 
Fully covered wooden box used earlier with 1-inch thickness. 	Redesigned wooden box with 0.75-inch thickness. 

Fig. 6. Improvements made after MFCA implementation.

Table 7
Summary of implemented solutions and quantified benefits obtained after MFCA implementation.

QC	MFCA Solution implemented	Type of benefit achieved	Investment (INR)	Resources saved in terms of Material/ Energy/System cost	Annual savings (in INR) (1 USD = 69.55 INR)
1. Raw material stockyard	The wall thickness eccentricity of the raw material tube was reduced from 0.40 mm to 0.15 mm.	Due to material saving, 9.75 INR/tube is saved. Approximately 19,500 tubes are consumed per month. Hence, 190,125 INR is saved per month.	0 INR (Requirement specified to the suppliers)	Material saving: Iron	2,281,500
2. Lubrication	Stage 1: Cleaning the individual raw material tube with pressurized water. Stage 2: Cleaning the lot of raw material tube by pressurized air before putting it in the acidic bath.	The usability of acid bath increased for a longer time period.	___	Material saving: Chemicals	___
3.1. Pointing	Length of pointed end of the tubes was reduced from 8 inches to 6 inches.	Due to material saving, 5.70 INR/tube is saved. Approximately 19,500 tubes are consumed per month. Hence, 111,150 INR is saved per month.	175,000	Material saving: Iron	1,333,800
3.2. Cold drawing	1. Electric proximity (inductive sensor) switch was introduced to avoid machine running in the unloaded condition.	Approximately 450 kWh/month/draw bench is saved by implementing the solution. Total 10 draw benches are present in the cold drawing process. Electricity is charged at the rate of 6.80 INR/kWh. Hence, 30,600 INR is saved per month.	12,000	Energy saving: Electricity	367,200
	2. Inclined plates with small stands were attached on the sides of the oil tank so that the excessive oil is restored back into the tank.	Approximately 25 kg of oil/month is prevented from being wasted by implementing the solution. Drawing oil is procured at 270 INR/kg. Hence, 6750 INR is saved per month.	10,000	Material saving: Oil	81,000
3.3. Heat treatment and straightening	1. Loading 2 Mt/h at furnace was done instead of 1 Mt/h. Also, the furnace was shut down when there is no load.	After MFCA implementation, loading in the furnace is now approximately 6,00,000 kg/month. Heat treatment cost is reduced from 2.21 INR/kg to 1.60 INR/kg.	___	Energy saving: Electricity, natural gas	[(2.21−1.60) INR/kg * 6,00,000 kg * 12 months] = 4,392,000
	2. Pneumatic cylinder was introduced due to which three persons were required for unloading instead of six.	By introducing pneumatic cylinder monthly expenditure of 3 workers is saved. The monthly wage of a worker is	50,000	Resource saving: Manpower	468,000

Table 7 (*continued*)

QC	MFCA Solution implemented	Type of benefit achieved	Investment (INR)	Resources saved in terms of Material/ Energy/System cost	Annual savings (in INR) (1 USD = 69.55 INR)
		13,000 INR. Hence, 39,000 INR is saved per month.			
	3. For the elimination of the overheating problem, one extra cooling zone was introduced which increased material loading by 50%.	Additional loading is approximately 2,00,000 kg/month. Treatment cost was reduced from 6 INR/kg to 2.75 INR/kg.	35,000	Energy saving: Electricity	[(6−2.75) INR/kg * 2,00,000 kg * 12 months] = 7,800,000
	4. C.L.I.T. (cleaning, lubricationinspection, tightening) was introduced due to which breakdowns got reduced by 50%.	The utilization increased due to less breakdown. 15,000 kg/month of material was loaded more in the saved 50 h.	0 INR (Training given to concern people)	Energy saving: Electricity	[2.75 INR/kg * 15,000 kg * 12 months] = 495,000
	5. The waste heat (250°) of effluent gas was tapped for pickling department instead of releasing in the air.	Approximately 5000 SCM PNG per month is saved by implementing the solution. PNG is procured at the rate of 38 INR/SCM. Hence, 1,90,000 INR is saved per month.	200,000	Energy saving: Natural gas	2,280,000
4.1. Cutting and deburring	1. Electric proximity (inductive sensor) switch was introduced to stop machine when on unload condition.	Approximately 675 kWh/month/ cutting machine is saved. Total 2 machines are present in this process.	2400	Energy saving: Electricity	[6.8 INR/kWh * 675 units saved * 12 months * 2 machines] = 110,160
	2. One vertical pneumatic cylinder is added for proper gripping.	1144 m of tube length is saved/month by implementing this solution. 40 mm/ tube is saved. Rate of 1 m tube is 48 INR. Hence, 5544 INR is saved per month.	1000	Material saving: Iron	658,944
4.2. Rust prevention coating	Wastage of oil was recovered by using tapered plate attached with oil tank which resulted in productivity improvement and reduction in waiting time.	Approximately 77 kg/month oil is prevented from being wasted by implementing the solution. Rust preventing oil is procured at 72 INR/kg. Hence, 6750 INR is saved per month.	10,000	Material saving: Oil	66,528
5. Inspection and marking	One marking slate was used at least 2 to 3 times instead of discarding it after single-batch use.	The consumption of marking slate per month is reduced to 40 slates from 100 slates. The cost of one marking slate is INR 131. Hence, 7860 INR is saved per month.	___	Material saving: Marking slate	94,320
6. Packing and dispatch	Wooden box thickness was reduced from 1 inch to 0.75 inches.	___	___	Material saving: Wood	600,000
Total			495,400		21,028,452

5. Results and discussions

MFCA is essentially a green productivity tool which focuses on improving productivity and minimizing waste. The results of the present study also show that SMEs can improve their financial and environmental performance by implementing MFCA. Several solutions have been implemented based on the identified areas of improvement. For example, during the MFCA study, it was discovered that a huge amount of waste was created in the form of end cuts of the tubes in the cutting and deburring process (QC 4). This was because the wall thickness eccentricity of tubes delivered by the vendors varied between 0.4 mm and 0.12 mm and the different length of mother tubes ordered were delivered unsegregated. Hence, it was decided by the MFCA implementation team to minimize wall thickness up to 0.15 mm as a part of the improvement measure (see Fig. 6). The team also instructed their vendors to deliver the mother tubes pre-segregated based on different length. This resulted in the reduction of end cut losses of tubes. Similarly, in QC 6, it was identified that redesigning the wooden box (from fully covered to partially covered) and reducing its thickness from 1-inch to 0.75-inch would result in substantial cost savings through reduced material usage in the packing and dispatch process. The redesigned wooden box (see Fig. 6) provides the same amount of damage protection during shipping. All the other benefits obtained after MFCA implementation are summarized in Table 7. The case enterprise had overall annual savings of 21.028 million INR (USD 302,350) with an investment of 495,400 INR (USD 7123). Additionally, the MFCA implementation team recommended some future steps to reduce environmental impact. The current waste handling practices and future steps are summarized in Table 8. Thus, indicating the ways of achieving both financial and environmental benefits through implementation of MFCA tool.

MFCA is also referred as a toolbox for achieving sustainability (Guenther et al., 2015). It assists in achieving financial sustainability by reducing the manufacturing cost through efficient resource use. Further, it helps in achieving environmental sustainability through reduction in material waste and emissions. To investigate sustainable performance of the enterprise, ROIC and total material cost on an annual basis was calculated before and after MFCA implementation. Fig. 7 shows the ROIC value of five financial years from 2011–12 to 2015–16. It can be seen that the ROIC improved from 12.12 to 15.68, i.e. by 29.37% with the implementation of MFCA. From the material consumption point of view (refer to Fig. 8), it can be observed that after MFCA implementation, the material cost reduced significantly from 491.9 million INR (USD 7,072,609) to 361.1 million INR (USD 5,191,948), i.e. by 26.58%. The savings illustrated in Figs. 7 and 8 during five years is inclusive of variations in the cost of input materials, energy (increased PNG and electricity cost), wastewater treatment cost, system cost (increase in wage rates) and so forth. Only minor variations have been observed in the costs which do not have a significant impact on the analysis. However, as a part of technical innovations, the MFCA implementation has assimilated a waste minimization culture in the enterprise. Thus, the study findings reveals that the

Table 8
Summary of current waste handling practices and future actions to increase environmental efficiency.

QC	Type of waste	Nature of waste (hazardous/non-hazardous)	Current waste handling practices	Future actions identified through MFCA to increase environmental efficiency
1	Material waste (steel strips, tubes etc.)	Non-hazardous	Sent to scrap dealer.	Stringent quality check should be performed so that the number of defective tubes arriving from the supplier side is reduced.
2	Waste acid (chemical sludge)	Hazardous	Sent to common effluent treatment plant.	Following measures could be taken to further reduce the frequency of acid bath changeover: (i) First, the tubes should be cleaned with warm water before cleaning them with pressurized air. A hot water generator could be deployed to heat the water to the desired temperature of around 50 °C. (ii) Second, brush cleaning of the tubes should be performed after pressurized air has been blown over the surface. Then, the tubes should be put in the acid bath. This will reduce the dust sticking at the upper surface of the tubes; thereby reducing the early contamination of the acids in the lubrication (pickling) tank. (iii) Instruments to measure parameters like temperature, Ph level indicators should be installed to improve efficiency of lubrication operation. (iv) The lubrication process should be done in a closed tank to minimize the evaporation of chemical sludge into the atmosphere.
3	Rejected tubes	Non-hazardous	Sent to scrap dealer.	100% Manual inspection should be done before the lubrication process.
	Sample tubes taken out for quality check	Non-hazardous	Sent to scrap dealer.	Statistical technique should be incorporated to determine optimal sample size for quality check.
	Used pointing die	Non-hazardous	Sent to scrap dealer.	High quality dies should be procured to retain its usability for a longer time period.
	Used grippers	Non-hazardous	Sent to scrap dealer.	High quality grippers should be procured to retain its usability for a longer time period.
	Used cold drawing die	Non-hazardous	Sent to scrap dealer.	High quality dies should be procured to retain its usability for longer time period.
	Used drawing oil	Hazardous Waste	Sent to oil recycler.	High quality synthetic oil should be procured to retain its usability for longer time period.
	Used ammonia	Hazardous	Mixed with products of combustion (exhaust) and let out to atmosphere.	Installation of air pollution control equipment could be done to control the emission of suspended particulate matter, ammonia and other chemicals directly into the air.
	Used descaling chemical	Hazardous		
	Used MS-wire	Non-hazardous	Sent to scrap dealer.	Structural changes in the furnace rail (where tubes are kept for heat treatment) can be made to eliminate the use of MS-wire for binding the tubes during the heat treatment.
4	Rejected tubes	Non-hazardous	Sent to scrap dealer.	Standard operating procedures should be adopted so that the rejection rate is minimized.
	Pointed end cuts of tube	Non-hazardous	Sent to scrap dealer.	Pointed end cuts to be sent back to suitable vendor for recycling.
	Used abrasive cutter	Non-hazardous	Sent to scrap dealer.	Used abrasive cutter to be sent back to suitable vendor for recycling.
	Used deburring tool	Non-hazardous	Sent to scrap dealer.	Used deburring tool to be sent back to suitable vendor for recycling.
	Used jigs tool	Non-hazardous	Sent to scrap dealer.	Used jigs tools to be sent back to suitable vendor for recycling.
	Used hydraulic oil	Hazardous	Sent to oil recycler.	Better quality hydraulic oil should be procured to retain its usability for a longer time period.
	Used pressure gauge	Non-hazardous	Sent to scrap dealer.	Used pressure gauge to be sent back to suitable vendor for recycling.
	Used rust preventing oil	Hazardous	Sent to oil recycler.	Better quality rust preventing oil should be procured to retain its usability for a longer time period.
5	Rejected tubes	Non-hazardous	Sent to scrap dealer.	Standard operating procedures should be adopted so that the rejection should be minimum.
	Cotton material	Non-hazardous	Waste discarded and sent to landfill site.	To reduce these waste, manual marking should be eliminated and electronic marking system should be adopted.
	Marking slate	Non-hazardous		
	Marking chemical	Hazardous		
6	HDPE	Non-hazardous	Waste discarded and sent to landfill site.	Use of plastic sheets for packaging should be completely eliminated; instead reusable/bio-degradable packaging materials can be adopted.
	Plastic sheets	Non-hazardous		
	Steel strips	Non-hazardous	Sent to scrap dealer.	

implementation of MFCA enables cost reduction through less material usage and reduced waste generation. Subsequently, this reduced material use and waste minimization in longer-term helped the enterprise in achieving their environmental and financial sustainability goals.

6. Conclusions

The sustainable performance of SMEs is important for the development of a country's economy. Though limited in resources, SMEs can still contribute towards sustainability through the adoption of green production techniques. MFCA is one such inexpensive green productivity tool that can be used for improving environmental and financial performance simultaneously. This article presented the application of MFCA tool in a steel pipe and tube manufacturing enterprise in India. The implementation of MFCA facilitated the case study enterprise to understand its productivity in terms of material flow. This paper also addressed the 'what' and 'how' research questions on MFCA implementation that prompted the purpose of this case study. The 'what' question is addressed by identifying the key improvement areas in the business process through MFCA implementation. The 'how' question is addressed by finding ways of improving these identified areas in the business process. MFCA facilitated the case study enterprise to

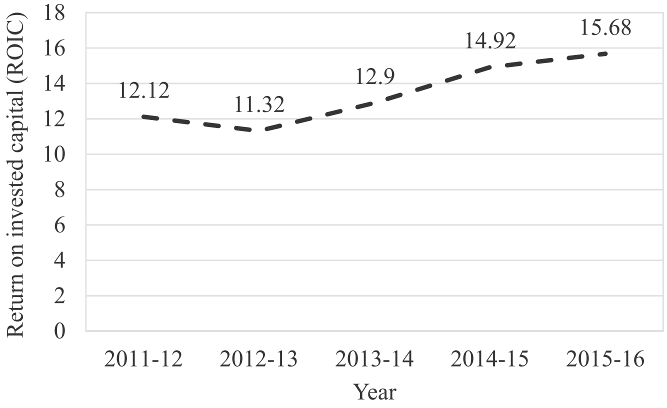


Fig. 7. Impact on ROIC through MFCA implementation.

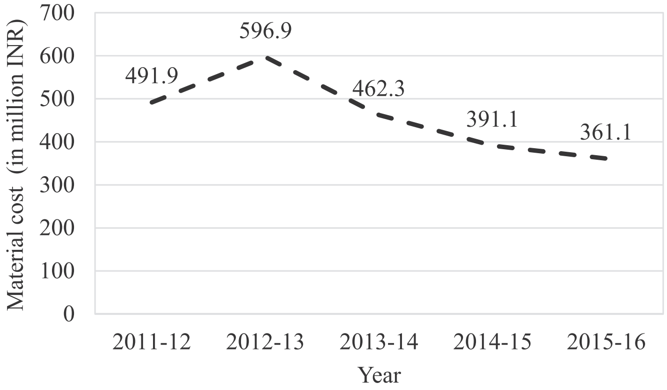


Fig. 8. Impact on material usage through MFCA implementation.

become competitive through informed material flows. The enterprise management was able to identify the losses and inefficiencies occurring in the production process. It also assisted the SME to achieve better profit margins for long-term business sustainability by reducing waste, resource consumption, and emissions.

Manufacturing of goods with standardised and sustainable production methods is essential for SMEs. The principles of productivity enhancement through process improvement, material and energy conservation tools are becoming more relevant in today's sustainable manufacturing context. Given the reluctance of SMEs to implement the MFCA tool (for various reasons as also discussed in Section 1), it is imperative to establish a conducive ecosystem to enable the adoption of MFCA tool among Indian SMEs. In this regard, the role of government is paramount. For instance, the government and policymakers may conduct suitable workshops, develop training courses, provide technical support, and share success stories of the benefits obtained through MFCA implementation. These measures can potentially motivate the top management and also enhance the technical knowledge of SME employees to support MFCA implementation. In this regard, the example of Japan is noteworthy. The "Environmental Management Accounting Promotion Project" launched in 2002 (by METI) has resulted in a countrywide implementation of MFCA in Japanese enterprises. Similar promotional events for SMEs can be initiated by the government and policymakers in India. Proper communication channels for publicity may also be set by the government and policymakers for encouraging Indian SMEs to implement MFCA.

6.1. Theoretical and practical implications

The current research work has both theoretical and practical implications. Following are the theoretical implications of the study: First, the present study attempts to fill the research gap quoted by Guenther et al. (2015) concerning the low academic publications of action-based research in MFCA literature. Hence, it makes a significant contribution to the emerging MFCA literature. Second, it provides detailed academic evidence of MFCA implementation process in an SME set-up, especially in context to steel pipes and tubes manufacturing enterprise that have been scarcely addressed in the literature. Third, by providing insights regarding adoption of MFCA tool in context of developing economy (i.e. India), the study extends the geographical scope of academic investigations related to MFCA; thereby addressing the call by Christ and Burritt (2016).

This study provides the following practical implications: First, the implementation steps demonstrated in the study will help the SME managers and practitioners to understand the effective implementation of MFCA tool. The current study exemplifies step by step MFCA implementation process for improving the firm's financial and environmental performance. Second, the present study sets an example to encourage other SMEs for becoming more environmentally conscious and economically sustainable. Third, government and policymakers, working towards establishing sustainable manufacturing practices in SMEs can introduce nationwide schemes to implement MFCA. Fourth, the results of this study will promote the adoption of MFCA in developing or low-income countries to show their contribution towards cleaner production. Lastly, with the advent of ISO 14052, the authors believe that the present case study provides useful implications for extending the MFCA application at the supply chain level. In the present study, it was identified that a huge amount of material loss occurring internally in the enterprise was caused due to the raw materials provided by the suppliers. Hence, the case enterprise contacted their mother tubes supplier in China for setting strict tolerance limit of the tube wall thickness eccentricity and getting the tubes sorted based on different length from the next delivery batches. Subsequently, the supplier of wooden boxes used for packing the finished product was also contacted to provide the redesigned boxes as suggested by the MFCA implementation team. Such collaboration and integration with suppliers are important in implementing MFCA at the supply chain level (Prox, 2015). Additionally, the information related to environmental and financial benefit of MFCA can be shared with the supply chain partners in order to collaborate and encourage them to implement MFCA in their enterprise.

6.2. Study limitations and future scope

Although the present study addressed newer insights into the MFCA literature, the research has few limitations that can be considered as agendas for future work. First, this study presented the application of MFCA that was limited to the manufacturing of a single product (precision steel tubes) having only 11 sub-process. Future research may be carried out to apply the MFCA tool in a more complex production structure or large scale enterprises. Second, this study focused on a single enterprise for MFCA implementation. Future studies could be carried out to determine whether the benefits of MFCA implementation vary across different geographical locations and different industry sectors. Third, as SMEs face many obstacles with regards to MFCA implementation due to their technical, financial, and time constraints, an empirical investigation to understand the reasons for resistance/barriers and adoption of MFCA in the SME context can be considered as another future area of research. Fourth, since LCA tool captures the overall environmental impacts of products and services, an interesting extension of this study would be to combine the extended MFCA tool with LCA so that environmental and economic aspects can be further addressed in detail simultaneously. Also, implementing MFCA at the supply chain level, particularly in the service sector, is another scope of the study for researchers.

Author contributions

Aditya Kumar Sahu: Writing- Original draft preparation, Formal analysis, Methodology, Investigation, Visualization, Writing - Review & Editing. R. K. Padhy: Conceptualization, Project administration, Supervision. Debabrata Das: Data Curation, Formal analysis, Methodology, Validation, Writing - Review & Editing, Supervision. Amitosh Gautam: Data Curation, Project administration, Resources.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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Appendix A. Supplementary data

Supplementary data to this article can be found online at https://doi.org/10.1016/j.jclepro.2020.123751.

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Glossary

hr: Hour
INR: Indian rupee
Kg: Kilogram
Kwh: Kilowatt hour
mm: Millimeter
MT: Metric ton
PNG: Piped natural gas
SCM: Standard cubic meter
SME: Small and medium-sized enterprise