Integration of Process Analysis and Decision-Making Tools for the Sustainability Improvements in Raw Rubber Manufacture

（天然ゴム製造における持続可能性改善のためのプロセス分析と意思決定ツールの統合）

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Doctor of Philosophy (Engineering)

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Abstract（Doctor）

Title of Thesis	Integration of Process Analysis and Decision-Making Tools for the Sustainability Improvements in Raw Rubber Manufacture (天然ゴム製造における持続可能性改善のためのプロセス分析と意思決定ツールの統合)

Approx. 800 words

Raw rubber manufacture is an industry mainly based in developing countries in South and South East Asia. It has been a prominent source which brings foreign revenue to such countries. Reported as material-, energy-, and labor-intensive, this industry has been confronted with high cost of manufacture, low cost efficiency and various environmental issues. Therefore, the main aim of my research has been addressing these issues through improving raw rubber manufacture to have less material and monetary losses, environmental and negative social impacts. Manufacturing major raw rubber products of crepe rubber, concentrated latex, and ribbed smoked sheets in Sri Lanka has been subjected to this research.

Firstly, crepe rubber and ribbed smoked sheet manufacture were analyzed using a novel method to reach the aim. This method deployed: 1) material flow analysis (MFA), material flow cost accounting (MFCA) and environmental life cycle assessment (ELCA) to quantify material flows and waste, monetary losses, and greenhouses gas (GHG) emissions, 2) Pareto and what-if analyses, information from field interviews and literature to develop improvement options; and 3) re-execution of MFA, MFCA and ELCA to foresee the degree of improvement. Simple cost benefit analysis was also employed to know the financial feasibility of improvement options. In terms of crepe rubber manufacture, water and chemical use found to be the factors affecting monetary losses whereas electricity had been a key driver of GHG emissions. While monetary losses were found negligible in ribbed smoked sheet manufacture, firewood use had been a major factor affecting GHG emissions. Based on field interviews and literature, viable improvement options were developed; for instance, installing water reuse system, re-determining dry rubber content and installing solar panels were proposed for reducing water, chemicals and electricity, respectively in crepe rubber manufacture. To reduce firewood use in ribbed smoked sheet manufacture, an efficient smoke house consuming less firewood was proposed. Improvement options were foreseen to be saving water, chemical, energy and firewood to give remarkable financial and environmental benefits for both manufacturing lines. Meanwhile, the simple cost benefit analysis indicated that all improvement options were financially feasible.

Secondly, the previous method was further modified to be applied to concentrated latex manufacture. Discounted cash flow analysis (DCFA) and greenhouse gas payback time (GPBT) were integrated in this regard for a detailed economic and environmental feasibility assessment. Novel loss reduction efficiency (LRE) index was also introduced to measure overall efficiency of improvement options. Rubber losses and chemical consumption were found to be main factors affecting monetary losses whereas electricity consumption was identified as a key driver of GHG emissions. Similar to previous research, applicable improvement options were proposed based on field interviews and literature. Extending sedimentation time during the addition of chemicals and installing trap tank were amongst the improvement options proposed for reducing chemicals and rubber loss, respectively. Installing inverters and solar panels were proposed to lower electricity consumption to alleviate GHG emissions. Results were promising as large proportion of monetary losses and environmental impacts were foreseen to be lowered by the proposed improvement options. As per DCFA and GPBT, proposed improvement options were found to be economically and environmentally feasible. Novel LRE index was proven to be effective as it could identified installing trap tank as the best option of all.

Not scrutinizing social impacts of natural rubber manufacture was a major lacuna in both methods; hence, thirdly, we tried performing a social life cycle assessment (SLCA). SLCA is a relatively new discipline and has no designated method or framework published yet. Therefore, a new method based on Analytic Hierarchical Process (AHP) was developed for conducting SLCA. Quantifiability of negative and positive social impacts, and foreseeability of the improvement in social aspect were the key features of this method. This method was used to scrutinize the social impact of workers at a raw rubber factory in Sri Lanka. Results claimed that health and safety, and social benefit/social security of workers were affected thereby jeopardizing working conditions, and health and safety of the country or area. Proposing countermeasures for the identified issues, the extent to which the said aspects can be improved was clarified.

Table of Contents

CHAPTER 1 General Introduction

CHAPTER 2 Financial and Environmental Sustainability in Terms of Process Analysis and Decision-Making Tools: A Study of Crepe Rubber Manufacture

CHAPTER 3 Financial and Environmental Sustainability in Terms of Process Analysis and Decision-Making Tools: A Study of Ribbed Smoked Sheet Manufacture

CHAPTER 4 Further Improving Financial and Environmental Sustainability in Terms of Process Analysis and Decision-Making Tools Integrated in a Method Based on Continuous Improvement Concept: A Case Study with a Crepe Rubber Factory in Sri Lanka

CHAPTER 5 Improving Financial and Environmental Sustainability by Combining Process Analysis Tools with Pareto, What-if, Economic and Environmental Feasibility Analyses: A Study of Concentrated

Latex Manufacture

CHAPTER 6 Social Life Cycle Assessment in Raw Rubber Manufacture

CHAPTER 1 General Introduction

1.1 Background

Raw rubber processing (also called natural or primary rubber processing) plays a critical role in the rubber product manufacturing sector by providing raw rubber in the required form. In Sri Lanka, the rubber sector ranked as the third largest foreign exchange earner with its exports contributing 122,074 million rupees (824 million USD) to the foreign exchange revenue in 2014 [1][2]. Furthermore, this sector has been a source of 300,000 direct and indirect job opportunities to Sri Lankans [3].

Fig. 1.1 outlines the journey of rubber products; Once latex is collected from rubber trees, it is processed into primary products, referred to as raw rubber, that are then utilized in different manufacturing industries to be reprocessed into value-added rubber products. Raw rubber products such as crepe rubber, concentrated latex, and ribbed smoked sheets (RSS) have been the principal raw materials of many value-added or secondary rubber products. Crepe rubber is in the form of pale yellow crinkled sheets and is high in purity; therefore, is used for shoe soles, medical and surgical items. Concentrated latex is in the liquid form and contains ca. 60% dry rubber acquired through centrifugation, i.e., separation of preserved field latex into two fractions; one containing ca. 60% dry rubber and other containing ca. 4-6% dry rubber. Concentrated latex is used for manufacturing dipped goods such as surgical gloves, condoms, infant pacifiers, etc. RSS are patterned brown sheets having a high tensile strength, low heat build-up and resilience; hence, it is used in producing tires, tubes, hoses and footwear.

Fig. 1.1. Journey of rubber products.

Production of raw rubber is a labor-, energy-, and material-intensive process, where a significant amount of electricity and thermal energy, fresh water, firewood, and chemicals are used at different stages of the manufacturing process (please refer to Fig. 1.2 for several snapshots within a crepe rubber factory) [4]. Electricity is mainly used in heavy-duty machinery, pumping water, wastewater treatment, and factory lighting. Meanwhile, thermal energy is used for rubber drying and is generated by firewood burning. Fresh water is an important material consumption factor. Water is essential for washing, factory cleaning, dilution of chemicals and field latex, and even for cooling machinery.

Furthermore, various chemicals including sodium bisulfite, acids (e.g., formic and sulfuric acid), bleaching agents, diammonium hydrogen phosphate, tetramethylthiuram disulfide and zinc oxide, and ammonia are used in manufacturing different raw rubber products [5][6][7][8]. Great deal of labor is required in raw rubber manufacture [5]; For instance, in crepe rubber manufacture, rubber feeding to machinery and adjusting rollers are done manually. Wet rubber laces are required to be back-carried to drying tower for drying after milling. Cleaning rubber sheets and visual grading are done by bare eyes; hence, are tiresome and laborious. Some tedious tasks are done by the workers in concentrated latex factories as well; cleaning tanks, bowsers and centrifuge bowls, and skim rubber processing are some of them. RSS manufacture require less labor compared to the preceding manufacturing lines where the laborious parts of which are milling (N.B. milling is done by hand-operated rollers which require a lot of effort in pressing RSS to the required form) and smoke-drying (i.e., drying RSS using smoke of rubberwood; this may take three to four days under frequent and thorough supervisions and inspections).

Raw rubber processing is confronted by low productivity, cost-ineffectiveness, and rising production costs [9][10]. Lack of material and energy efficiency, higher degree of wastes and losses, and rising cost of raw materials could be the main drivers of these challenges. Furthermore, raw rubber processing contributes to numerous environmental problems such as acidic wastewater discharge, obnoxious caused by rubber particles and chemicals, and greenhouse gas (GHG) emissions [11][12]. Meanwhile, societal issues are also evident; impaired working conditions, low wages and societal status, and pollution-created community unrests can be listed as a few of them [13]. Most of the workers in raw rubber sector are from poor and low educational backgrounds and so lack the knowledge about labor laws and policies; hence, they have been prone to labor exploitations in factories [13].

Fig. 1.2. Snapshots of a crepe rubber factory. (a) A female worker is doing visual-grading of crepe rubber, (b) A female worker operates a heavy-duty machinery called smooth roller, and (c and d) heavy-duty roller mills which require a lot of electricity, and fresh water for cleansing rubber and cooling.

1.2 Literature Review

Several initiatives have been taken to develop and apply some suitable strategies to address the issues concerned. In view of providing an economical solution for wastewater treatment, Kudaligama et al. [14] proposed and tested a cost-effective wastewater treatment plant. Deploying a water reuse facility at a Thai rubber factory, Leong et al. [15] studied on the reduction in water and treatment costs. Meanwhile, with the aim of resolving high firewood consumption in crepe rubber processing, Siriwardena et al. [16] tested four solar powered drying tower systems and a roof integrated solar air heater-storage system had been the most effective. Also, Rathnayake et al. [17] proposed a single day smoke dryer for RSS production and tested it applying to a factory in Sri Lanka. New system succeeded in drying RSS within a single day without compromising the standard quality of dried RSS. In addition, shortening of drying period had reduced cost of production as it saved firewood and the labor for handling. Tillekeratne [18] also investigated how to reduce the cost of production in a crepe rubber processing factory and found that processing unfractionated and unbleached crepe rubber had been the most effective in this regard, as it avoided the cost for the bleaching agent and saved extra labor cost associated with the removal of yellow fraction. Quantifying the material and monetary losses incurred in concentrated latex and block rubber production in Thailand, Department of Industrial Works [19] provided cleaner technology options that could be effective in reducing the observed losses.

In view of reducing the pollution associated with natural rubber processing, in-plant pollution control guidelines and wastewater discharge standards have already been established by central environmental authority of Sri Lanka [20][21]. Also, several studies have used life cycle assessment (LCA; also referred to as environmental life cycle assessment (ELCA)) based approaches to quantify and mitigate the environmental impacts (i.e., emissions) associated with overall natural rubber production process. For instance, Jawjit et al. [7] quantified the GHG emissions associated with the production of RSS, block rubber, and concentrated latex in Thailand. This study highlighted that fertilizer and energy use were the leading sources of GHG emissions in Thai natural rubber industry and such emissions could be reduced switching from synthetic fertilizer to animal manure, shifting from fossil fuels to renewable energy, and by energy and fertilizer efficiency improvement. Meanwhile, Jawjit et al [8], investigated the environmental performance of concentrated latex production in Thailand with use of LCA and proposed technically and practically viable cleaner technology options for improving the efficiency in consuming energy (i.e., electricity and fossil fuel), ammonia, and diammonium phosphate. GHG emissions in crepe rubber processing have also been appraised stressing the importance of using renewable energy [22]. Taking a different approach, Musikavong et al. [23] quantified the consumptive water use and water scarcity footprint of RSS production in different provinces of Thailand with an ultimate goal of preserving water resources. Whilst No records were found on social impact quantifications of raw rubber manufacture, several survey-based studies tried to assess the social impact of rubber estate workers [24][25].

All previous studies have taken only a partial approach by investigating either the economic or the environmental aspect of the raw rubber manufacture. There have been no studies on the efficiency of the entire manufacturing process nor social impact incurred by raw rubber manufacture. Therefore, this study aims to develop a sustainable manufacturing process in raw rubber processing industry using four novel methodical hierarchies that could be adopted by any other industry. First three methods were based on the process analysis tools of material flow analysis (MFA), material flow cost accounting (MFCA), and ELCA. Unlike previous studies (i.e., Ulhasanah et al [26], Nakano et al. [27], and Schaltegger et al. [28]) that combined MFA, MFCA, and ELCA, the present study took another step further by integrating Pareto, What-if, simple cost benefit, and discounted cash flow analyses into the said methodologies. Further, they propose a concrete framework for conducting and continuing an improvement process at a facility for efficient management. In view of knowing to social impact of raw rubber manufacture, fourth method is proposed for conducting a social life cycle assessment (SLCA). Unlike the SLCA methods published in literature (e.g., Hosseinijou et al. [29], Manik et al. [30], Franze et al. [31], Yıldız-Geyhan et al. [32], Prasara-A et al. [33], etc.), it could appraise both positive and negative social impacts of a manufacture and foresee the degree of improvement of its social dimension in numerical terms.

These methods are deployed across crepe rubber, concentrated latex and ribbed smoked sheets manufacturing lines in Sri Lanka (Please refer to forthcoming chapters for more details on these manufacturing lines). Sri Lanka holds a significant position in the world rubber manufacture as it ranks the eighth and sixth largest producer and exporter of rubber respectively [4][5]. Being renowned for its high-quality rubber, Sri Lanka currently holds ca. 125,645 ha of rubber land area which is ca. 2% of its size [6]. Rubber industry is the second major crop-based industry in island and had brought 25.6 million USD of foreign revenue in the year of 2016 by merely exporting raw rubber products [4]. Moreover, rubber industry provides over 300,000 job opportunities to Sri Lankans across various professions and walks of life as mentioned earlier.

Fig. 1.3 outlines the structure of the thesis tendering the essence of each chapter. Chapter 1 had been dedicated for providing a brief overview of the followings: 1) raw rubber manufacture and its issues, 2) literature addressed these issues; and 3) lacunas of literature which motivated us to do this research project. In the next chapter (Chapter 2), we introduce our first novel method which integrates MFA, MFCA, ELCA, and Pareto, What-if and simple cost benefit analyses to improve financial and environmental sustainability of crepe rubber manufacture. Four crepe rubber factories have been subjected to this research. The same method is applied to RSS manufacture in Chapter 3. The required data were extracted from three RSS factories in Sri Lanka. In Chapter 4 we try to further elevate financial and environmental sustainability in crepe rubber manufacture deploying our second novel method (N.B. this method is an enhanced version of the first method by adding continuous improvement concept). This time only one factory was subjected for the analysis. In Chapter 5 we further enhance our second method to formulate a third novel method. Here, the simple cost benefit analysis in previous methods is replaced with discounted cash flow analysis and greenhouse gas payback time and novel loss reduction efficiency index to extract more information on financial and environmental feasibility, and overall efficiency of improvement options. So far, financial and environmental sustainability of raw rubber manufacture had been the focus; hence, we scrutinize social sustainability of raw rubber manufacture in Chapter 6. Novel method for SLCA is formulated and applied to a crepe rubber factory in Sri Lanka, in this regard. Chapter 7 concludes the thesis with highlighting the followings: 1) main findings in each chapter and their importance to raw rubber manufacture, 2) possible barriers that may hinder improvement procedures discussed herein; and 3) avenues for future research in rubber sector as whole.

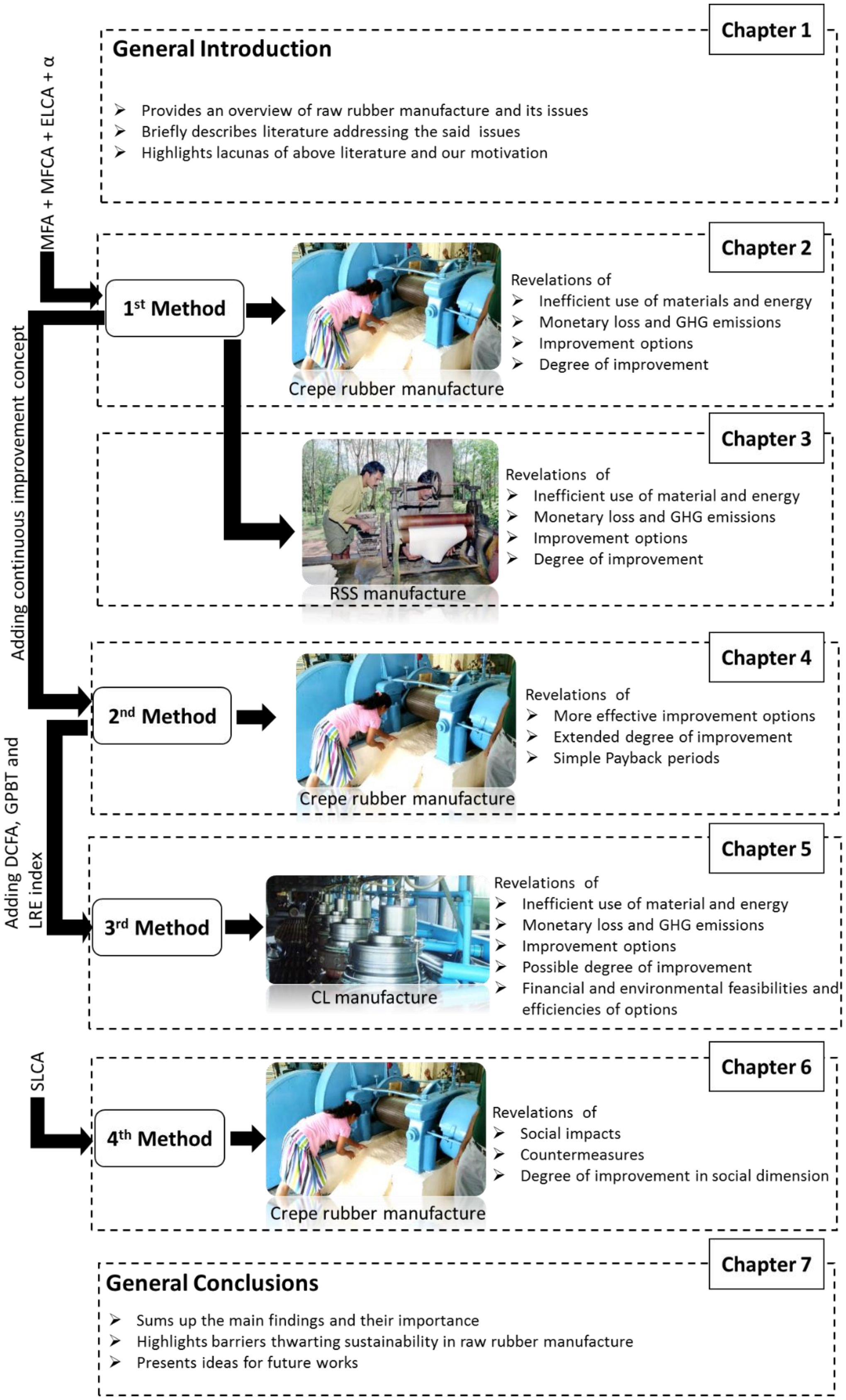

Fig. 1.3. Outline of the thesis. MFA, MFCA, ELCA, SLCA, DCFA, GPBT and LRE index refer to material flow analysis, material flow accounting, environmental life cycle assessment, social life cycle assessment, discounted cash flow analysis, greenhouse gas pay beck time, and loss reduction efficiency index, respectively. Alpha (α) stands for Pareto, What-if and cost benefit analyses integrated in first method.

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CHAPTER 2 Financial and Environmental Sustainability in Terms of Process Analysis and Decision-Making Tools: A Study of Crepe Rubber Manufacture

2.1 Introduction

The natural rubber (NR) industry plays a critical role in the economies of many developing countries, particularly in Asia where 92% of world`s NR produced [1]. NR industry in Sri Lanka is the third largest export earner of the country [2]. In 2014, NR exports contributed LKR 122,074 million (USD 824 million) to Sri Lanka's foreign exchange revenue [3] accounting for about 8% of the total annual export value [4]. Furthermore, the NR sector has provided over 300,000 direct and indirect employments to Sri Lankans across various walks of life [5].

In NR production, rubber trees are tapped to collect fresh latex which is then processed into primary rubber products named as raw rubber [e.g., crepe rubber, concentrated latex, ribbed smoked sheets (RSSs)]. Subsequently, these raw rubber types are reprocessed into secondary rubber products (value-added rubber products) such as tires, tubes, gloves and condoms [6]. Of the raw rubber types, crepe rubber is considered to be the purest form of natural rubber available in the market [7]. Sri Lanka is the world`s leading crepe rubber producer for the international market with a production of about 46,502 MT per year, which is about 31% of the overall rubber production in the country [8]. Crepe rubber acts as a foundation of many pharmaceutical and surgical items which are in contact with human body [7][9].

Being a long-term tree crop, rubber cultivation is considered as an environmental friendly process with low tech involved. A rubber tree fixes about 1 MT of CO2 in its 30 year economic lifespan and even resource poor farmers could cultivate rubber in tropical climates [10]. In Sri Lanka and elsewhere, processing of latex to RSS is mostly done in small scale within the farmland. Crepe rubber manufacturing in Sri Lanka is done in factories built over 50 years ago, hence considered as a labor-, energy-, and material-intensive process in present day context. Compared to other categories of raw rubber, a considerable extent of skilled labor is involved in the processing of crepe rubber [7]. A large amount of electricity is needed to run the heavy-duty machinery used for milling, water pumping, wastewater treatment, and factory lighting. Furthermore, heat energy generated from firewood is used to dry crepe laces in drying towers. Fresh water is one of the key material inputs in crepe rubber manufacturing. It is mainly used to dilute the latex and chemicals, to wash crepe sheets during milling, to avoid heat build in machinery and for their cleaning. In different stages of crepe rubber manufacturing, chemicals are used as preservatives, bleaching agents, and coagulants [7] [11].

On this background, crepe rubber processing suffers from low level of labor productivity, lack of cost effectiveness and rising cost of manufacture [12][13][14][15].

Obviously, these issues are connected with low level of efficiencies in material, labor and energy use, high degree of waste and losses and rise in cost of all inputs. Furthermore, high level of water use and effluent discharge in crepe rubber manufacturing would create environmental issues, if not addressed properly. Discharge of untreated rubber factory effluent to the environment may lead to water pollution, malodor and crop damage whilst high level of water consumption would result in intensified depletion of adjacent water resources [16]. Other environmental issues related to crepe rubber production include emissions that occur from heavy electricity and firewood use [17][18]. Nevertheless, crepe rubber production in the country should continue to meet the international demand and to maintain the in-country economy. Therefore, it has become vital to develop and implement sustainable production strategies in crepe rubber production for its long-term existence.

For providing a cost-efficient solution to high firewood consumption, Siriwardena et al. [19] investigated four solar powered drying tower systems for the crepe rubber drying process and concluded that a roof integrated solar air heater-storage system is effective in this regard. Also, Tillekeratne [20] highlighted the steps taken by the Rubber Research Institute of Sri Lanka (RRISL) to minimize the cost involved in Sri Lankan crepe rubber manufacturing. Production of unfractionated and unbleached crepe rubber has been identified as an effective means in this regard due to avoidance of cost for the bleaching agent and saving on extra labor associated with the removal of the yellow fraction. Furthermore, RRISL has introduced a low-cost biological wastewater treatment system for rubber factory effluent and this has already been installed in many Sri Lankan crepe rubber factories [21]. Applying Covered Activated Ditch type reactors, Kudaligama et al. [22] tried to minimize the cost associated with a biological wastewater treatment system. Also, Kudaligama et al. [23] had investigated how nitrogen and other chemicals in the effluent affect the efficiency of wastewater treatment plants installed in crepe rubber factories. Based on a water sample analysis, Gamaralalage et al. [24] assessed the effectiveness of available wastewater treatment plants in Sri Lankan NR sector. Identifying that the wastewater discharged from crepe rubber factories still contains harmful nitrate-nitrogen concentrations though being treated, the necessity of cost effective and efficient de-nitrification process in order to convert nitrate-nitrogen into nitrogen gas was stressed. Nevertheless, strict guidelines and standards have already been imposed by the central governmental authority of Sri Lanka to reduce the pollution level associated with the wastewater of crepe rubber factories [25]. Meanwhile, Peiris [12] reported some steps taken by a crepe rubber factory to reduce cost of production and to improve the quality of product, i.e., crepe rubber. Training on factory upkeep and the 5S concept had been effective in motivating the employees to reduce wastewater and keep the workplace clean while enhancing profits. In an attempt to quantify GHG emissions associated with crepe rubber manufacturing, Kumara et al. [18] identified the electricity consumed by machinery as a prominent factor and noted that replacing such energy requirements with the electricity from renewable energy sources could be a sensible move toward curbing

GHG emissions. However, no studies on process analysis of crepe rubber manufacture have been reported.

Though have not so far been used in the raw rubber manufacturing, various process analysis techniques have been developed and deployed to assess the performance efficiencies under different segments in the sustainability. In particular, Material Flow Analyses (MFA) and Material Flow Cost Accounting (MFCA) deal with the economic aspects whilst Life Cycle Analyses (LCA) extend the above two analyses to cover the environmental aspects of the sustainability. For instance, MFA and MFCA have been applied for Cassava processing [26], meat processing [27], textile production [28] and wood products manufacturing in Thailand [29], micro-brewery [30] and paper manufacturing in South Africa [31], and small medium scaled enterprises (SMEs) in Malaysia [32]. In all these studies, reduction in wastes and improvement in cost efficiency have been focused pinpointing the deficiencies in respective processes and ultimately enhancing profits. Nevertheless, the combine use of MFA, MFCA, and LCA have been limited to few studies. Ulhasanah et al. [33] used this combination to evaluate the environmental and economic performances in cement production of Indonesia. As a result, a new design for economically viable and less polluting cement production system was proposed. Nakano et al. [34] developed a supply chain collaboration model for enhancing improvement activity of product environmental performance of which the above-mentioned tools were in its process analysis stage. Further, Schaltegger et al. [35] used MFA, 1MFCA, and LCA to identify the process deficiencies in a beer brewing facility in Vietnam against an equivalent facility in Germany. Overall, the use of the said tools had confined to appraising the current environmental and economic situation of the respective processes in all these studies; however, there are some lacunas in assessing the financial worthiness of proposed changes in the systems.

Techniques like cost-benefit analyses are used to determine the worthiness of an investment against the financial returns [36]. For instance, Doorasamy [31] integrated cost-benefit analyses with MFCA to identify the payback period of the boiler-related modifications proposed for a paper manufacturing company in South Africa. Also, a technique like Pareto analysis can be used to distinguish the key tasks having significant impact on the ultimate effect [29]. For instance, it has been used with MFCA to select the key loss cost factors in a meat processing factory [27], a textile factory [28], and a wood products manufacturing company [29] in Thailand. Similarly, one-way sensitivity analysis (what-if analysis) can be deployed to identify the most sensitive factors affecting the outputs [37], hence can be used in combination of MFA [38]. However, the application of these techniques had been constrained to either MFA or MFCA missing out the environmental aspects.

Despite the above approaches to assess the overall efficiencies in production models, all previous studies on crepe rubber manufacture have been confined to a partial approach dealing only with either single or few issues neglecting others (e.g., either an economic or environmental aspect). No studies to date have simultaneously evaluated the material consumption, wastes, losses and environmental burdens of the entire crepe rubber manufacturing process for identifying their economic and environmental hotspots. Although rubber cultivation is obviously an environmentally beneficial process having negative CO_2 emission, such importance cannot be highlighted with no proper knowledge on the sustainability in raw rubber processing. Therefore, an assessment on the financial and environmental sustainability in the manufacturing process of crepe rubber was the focus in this study using the techniques of MFA, MFCA and LCA in view of improving the current manufacturing process to be more cost-efficient and environmentally friendly. Rather than merely combining MFA, MFCA, and LCA, we used integrated approach combining Pareto and what-if analyses with these techniques to identify the economic and environmental hotspots of the system for an efficient management. Further, we extended the combined use of MFA, MFCA, and LCA with cost benefit analyses to predicate the degree of improvement with financial feasibility when the identified hotspots are addressed. Since the ultimate target is only to develop energy efficient, less polluting and financially more viable process for manufacturing of crepe rubber, social aspects of the sustainability were not in the focus. More specifically, the study firstly aims to quantify all resources used, wastes, mass flows, monetary losses, and Green House Gases (GHG) emissions in the current crepe rubber manufacturing system and secondly, to identify potential options for improvements in the system and finally, to quantify the impacts of such improvements in terms of financial and environmental attributes.

2.2. Crepe Rubber Manufacturing Process

The crepe rubber manufacturing process is illustrated in the flow chart shown in Fig. 2.1. Details of key steps are given below.

Rubber latex collection (Rubber tapping & Transportation)

With periodically made incisions on the bark of the rubber tree, white-colored field latex is collected firstly into the cups hanged on the tree close to the incision and then to buckets. Before transportation to the factory, sodium sulfite is added as an anticoagulant to preserve the latex.

Standardization

Sooner the field latex arrives at a factory, be its dry rubber content (DRC) measured. Then, the latex is sent to bulking tanks, to which sodium bisulfate and water are added as a preservative and a diluent, respectively, considering the DRC value. The white and yellow fractions are extracted because of partial coagulation. The yellow fraction is 10% of the DRC [7]. After fractionation, the white fraction is passed to settling tanks where coagulation occurs. However, the yellow fraction is sent directly to the mill for initial processing and then drying.

Coagulation

At this stage, formic acid (coagulant) and a bleaching agent are added to the white fraction. Moreover, some water is added to dilute the chemicals for consistent dispersion within the white fraction. The mixture is left for some time to coagulate and then is removed in cube-like pieces.

Milling

During milling, pieces of the coagulum are passed through a series of two roller mills to produce thin rubber laces. Firstly, coagulum is directed to a mill with two horizontally grooved rollers called macerator. Secondly, the macerated pieces are sent through a mill with two diamond grooved rollers to get thin rubber sheets as output. Finally, these sheets are passed through two smooth rollers to get rubber laces with minimum perforations.

Drying

Milled laces are carried over to a drying tower and left for 3 to 4 days for drying. Radiators that circulate boiled water generate the warm air in the drying tower. Rubber wood is used in furnaces to boil the water.

Folding

Dried laces are folded into stacks that weigh 25 kg. Before folding, the quality of laces is checked and pieces of dirt that affect the quality of the final produce (crepe) are removed.

Dry blanket milling

In this process, the 25 kg stacks are passed through a set of two horizontally grooved rollers twice to shape the rubber into a blanket form.

Cutting

During cutting, the blankets are trimmed into a buyer-specified rectangular-shaped size. Furthermore, dirt removal is performed again on the trimmed rubber. The output after this stage is deemed crepe rubber.

Packing

In this stage, the crepe rubber is graded via simple visual assessment by the workers and then packed into 25 kg or 50 kg bundles. In most factories, only the highest quality grade, 1X, is packed using low-density polyethylene (LDPE) films whereas inferior grades are tightened with 1 or 2 rubber strips of the same grade.

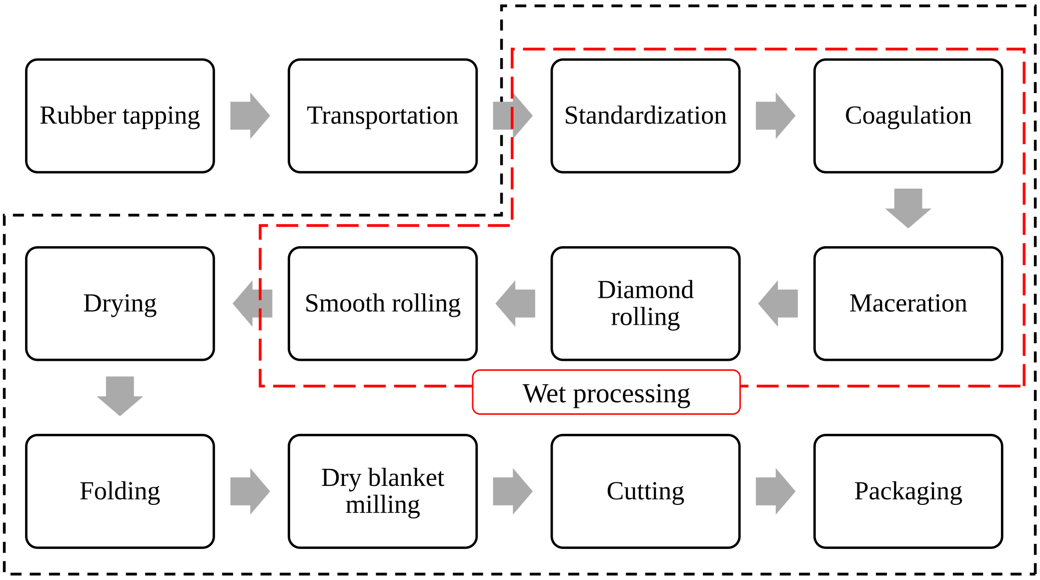

Fig. 2.1. Crepe rubber manufacturing process with the system boundaries; red dashed line for wet processing activities and black dashed line for the overall study boundary.

2.3. Materials and Methodology

2.3.1. Goal Definition

The study comprised three steps to meet the objectives: (1) investigation of the current manufacturing process through quantification of the material consumption and waste, monetary losses, and GHG emissions, (2) identification of problems and proposal of the most feasible improvement options and, (3) validation of improvement potentials. Basic steps and how various tools and techniques were integrated in the study are illustrated in the Fig. 2.2. Furthermore, it offers an insight into the data inputs required by each tool or technique and the corresponding outputs. If briefly explained, in the step 1, MFA was initially conducted in an audited factory to get material flow data. Then, based on MFA data, MFCA and LCA were conducted to assess the monetary loss and Global Warming Potential (GWP) in terms of GHG emissions, respectively. In step 2, such information was used to identify key loss cost and GWP factors via Pareto and what-if analysis, respectively. Also, we referred to field interviews and literature to identify easily reducible factors as well as viable improvement options. In step 3, the improvement potentials of such options were quantified in isolation and collectively by running MFA, MFCA, and LCA. Thereafter, we deployed a cost benefit analysis to get an insight into the feasibility of the adoption improvement of options. Further details on the tools and techniques used under different steps are given in the following sections.

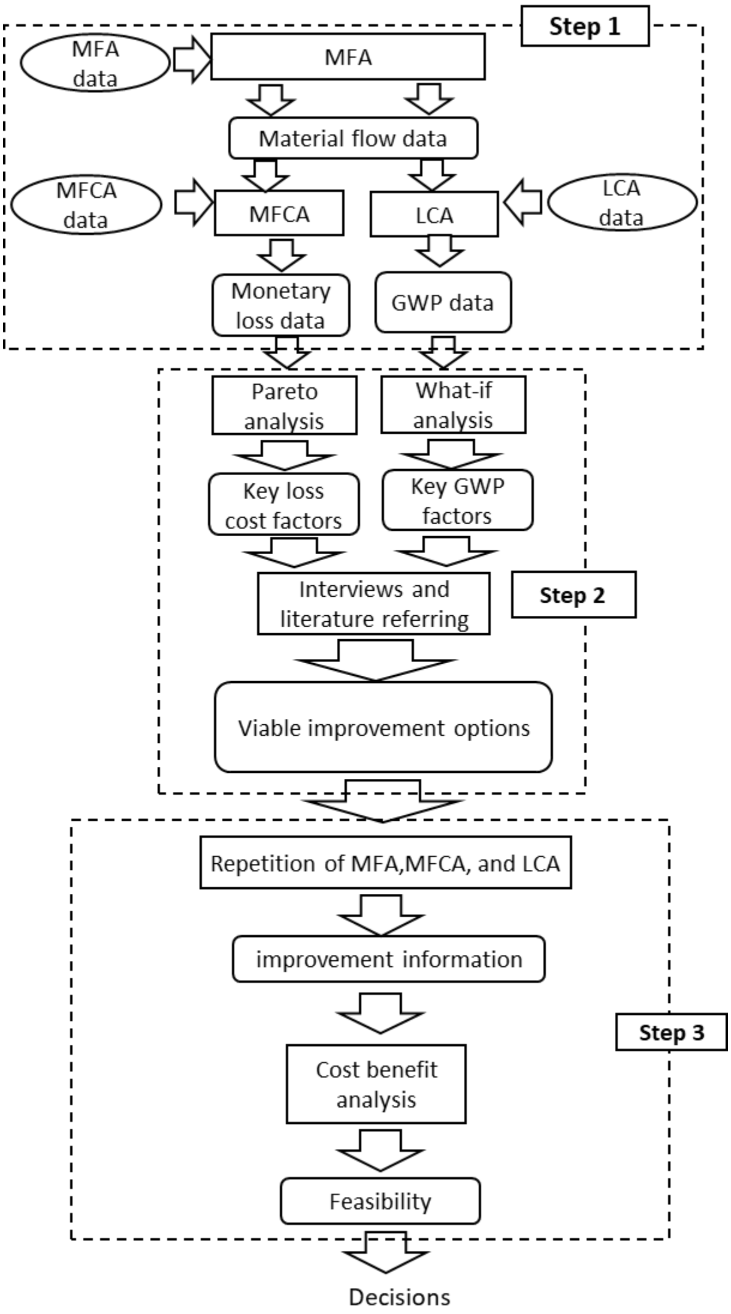

Fig. 2.2. Overview of the research methodology. Ovals depict the raw data inputs while the rounded rectangles denote the outputs. Rectangles represents the tools and techniques used. Codes MFA, MFCA, and LCA denote material flow analysis, material flow cost accounting, and life cycle assessment, respectively.

2.3.2. Quantification of Materials Involved (Step 1)

In this step, we employed MFA, MFCA, and LCA to quantify material consumption and waste, monetary losses, and GHG emissions, respectively.

2.3.2.1. System Definition

The system boundary that determined the unit processes included or excluded of this study, is demonstrated in Fig. 2.1. Activities carried out in rubber cultivations remained outside the system boundary, for the reason of their high level of temporal and spatial variability that demands separate study. In addition, the rubber tree had been identified as a source of carbon fixation [10]. To be more specific, net CO_2 emissions from plantations remain negative in general even after the CO_2 emissions bound with fertilizer consumption and latex transportation are included (for more details please refer to results and discussions section). Despite the sustainability of rubber cultivation, the system efficiency of crepe rubber manufacturing of which vast amounts of materials and energy are in use, are unknown, hence, was the sole focus of this study. Therefore for handling the in-plant assessment in crepe rubber factories, we used a gate-to-gate system boundary in deploying MFA, MFCA, and LCA as demarcated by a black perforated line in Fig. 2.1. This boundary covers all activities starting from the field latex entering from the gate of the factory to the dispatch of the final product from the factory gate. Specifically, it covered from the “standardization” to the “packaging”. In MFCA, we combined standardization, coagulation, maceration, diamond rolling, and smooth rolling into one processing unit named as “Quantity center No. 1” (QC1) to make calculations less complicated, and labeled this conglomerate as “wet processing.” Rest of activities were separated into another five processing units named as quantity centers 2-6 for drying (QC2), folding (QC3), dry blanket milling (QC4), cutting (QC5) and packaging (QC6), respectively. For LCA calculations, we considered external activities such as electricity generation, chemical production, and LDPE manufacturing.

2.3.2.2. Functional Unit

All the parameters used in MFA, MFCA, and LCA for both production lines were evaluated considering a functional unit of 1 MT of dry rubber input. In the case of MFA, we considered wet weight for latex containing 1 metric ton (MT) of dry rubber.

2.3.2.3. Data Collection

Data were collected by visiting four crepe rubber factories (factories A, B, C, and D) in Sri Lanka, all of which belonged to the three major rubber producing districts namely, Kalutara, Kegalle, and Ratnapura. In total, these districts account for about 75% of the total rubber land area in Sri Lanka. Assessments on the use of water, electricity, LDPE and rubber throughputs were taken as onsite measurements. Ash content of the rubber wood was determined through a laboratory analysis of a wood sample. Information on dry rubber content (DRC), chemical use, and rubber losses were collected from factory logbooks and through interviews carried out with factory workers, officers, and managers. Cost data on field latex, chemicals, labor, and LDPE films were extracted from factory accounts. Meanwhile, the unit cost for electricity was taken referring to the home page of the Ceylon Electricity Board. Further, costs involved in machinery depreciation and maintenance were collected via interviews with factory officials. Nevertheless, data required for MFCA and LCA in factory B could not be collected because its operations were abandoned due to the insufficient availability of latex during the study period. Therefore, the MFCA and LCA analyses were based entirely on data from factories A, C, and D. However, all factories had similar production capacities, processes, and general practices, except water supplies. In factories A and B, water was pumped using the gravity whereas C and D used electric water pumps.

Emission factors required for LCA calculations were obtained from literature and are summarized in Table 2.1. Having no previous studies and data, the emission levels of bleaching agent and wastewater treatment plant were considered as zero.

Table 2.1 Emission factors used in GWP calculations. Code LDPE refers to low-density polyethylene.

Activity	Gas	Emission factor	Unit	Reference
Production of sodium bisulfite		0.44	kg CO2e	[39]
Production of formic acid		2.51	kg CO2e	[39]
Production of LDPE films		2.00	kg CO2e	[40]
Wood use	CO_2 CH_4 N_2O	110 30 4	$kgCO_2/TJ$ $kgCH_4/TJ$ kgN_2O/TJ	[6]
Generation of electricity (Sri Lanka)	CO_2 CH_4 N_2O	0.417247633 1.64405E-05 3.28811E-06	$kgCO_2/kWh$ $kgCH_4/kWh$ kgN_2O/kWh	[41]

2.3.2.4. Material Flow Analysis (MFA)

MFA is a systematic assessment of the flows and stocks of material within a system, defined in a space and time [38]. When MFA is applied to a manufacturing system, it quantifies the mass flow of materials to locate and examine inputs, partitioning, stocks, outputs, and significant sources of waste materials in the factory [42]. MFA follows the mass balance principle: input mass is equal to output mass [26].

For MFA analyses, STAN 2.5 software [43] was used to work on uncertainties in the input-output data or flows and e!Sankey software [44] to develop Sankey diagrams. Initially, an MFA diagram was constructed for each factory using STAN 2.5 and then, all MFA diagrams were combined into a common material flow diagram where all the flow values were aggregated using mean ± relative standard deviation (RSD). Finally, a Sankey diagram (Fig. 2.3) was constructed with e!Sankey software with flow values in common MFA model.

2.3.2.5. Material Flow Cost Accounting (MFCA)

MFCA is an environmental management accounting tool that simultaneously involves the enhancement of economy and reduction of environmental impact [45][46]. MFCA quantifies the flows and stocks of materials in a production line in both physical and monetary units and provides information on costs associated with both products and material losses (e.g., waste, air emissions, wastewater) of which the organization is unaware [46]. In other words, MFCA makes physical and monetary losses at each process visible in numbers, thereby helping the organization in identifying problems and recognizing the necessity for improvements.

In MFCA, cost quantification was based on two types of product costs: positive product cost and negative product cost. Positive product cost represented the cost that was put into the finished product whereas negative product cost denoted the monetary value of wasted or recycled items (e.g., material losses, gaseous emissions, wastewater) [47]. The calculation process was conducted under four categories of cost information, i.e., material cost, system cost, energy cost, and waste treatment cost, by allocating them to the product (positive product costs) and waste flows (negative product costs or loss costs) in MFA [48]. Herein, the input material, system and energy costs were multiplied by the percent of material loss by weight in each processing unit or QC per 1 MT of rubber input to gain negative material, system and energy costs, respectively. However, waste management costs were solely allocated to negative product costs [26][48].

Furthermore, MFCA considered three types of materials for its calculations [49]; 1. Raw materials, 2. Auxiliary materials, 3. Operating materials. Raw materials were the main source of the end product, whereas auxiliary materials were the materials added to raw materials to produce end products. Operating materials were the materials that were essential to produce end products but completely wasted as wastewater or emissions after processing (e.g., water for machinery cooling).

In the analyses, a cost flow model was prepared for each factory and all such cost flow models were combined into one by aggregating each flow value to represent mean ± RSD using Excel software. Then, the final MFCA diagram (Fig. 2.4) was constructed using e!sankey software with the values generated in the combined model.

2.3.2.6. Life Cycle Assessment (LCA)

LCA is a tool that measures the overall environmental burden of products and services to promote a better understanding of possible environmental impacts [50]. It is a systematic assessment that follows a certain framework (e.g. ISO 14001, CML) based on a functional unit and a system boundary determined according to a goal and a system definition [50][51]. Most common areas that many LCA studies focus on are global warming potential (GWP), acidification, eutrophication, ozone layer depletion, and human toxicity [52]. However having no sufficient data, only the GWP index was used in this study by assessing the extent that crepe rubber processing contributes to global warming through emitting GHGs. To calculate GWP, we followed a model mentioned in Jawjit et al. [6] or we simply multiplied the conversion factor observed in "kg CO2e per unit" by the level of activity. Due to unavailability of emission factors for bleaching agent manufacture and wastewater treatment in crepe rubber processing, we had to consider the effect of them to be negligible. As the firewood was from the rubber trees that were replanted, CO_2 emissions incurred by firewood burning also had to be excluded from overall emissions [6]. The data compiling and GWP model calculations were carried out using Excel spreadsheets. First, activity based GWPs and the total GWP in each factory were quantified. Then, those GWPs were compiled to determine the mean values and RSDs that represent the overall crepe rubber production system in Sri Lanka.

2.3.3. Proposal of Improvement Options (Step 2)

This step had two objectives. The first was to identify the most influential factors that affect negative product costs and GWP. The second was to identify easily reducible factors and viable improvement options. For the first objective, Pareto and What-if analyses were used. Here, we deployed Pareto analysis to identify the most influential negative cost factors of each factory. Pareto analysis is a decision-making technique used for selecting several tasks that affect significantly on overall effect. Based on Pareto principle that assumes 80% of problems result from 20% of causes, we built up Pareto diagram (Fig. 2.6) to find the 20% of negative cost factors that cause 80% of the total negative product cost, in each factory. This diagram is a combination of both bars and a line graph. Bars represent the individual values of negative cost factors in descending order whilst the line represents the percentage achievement in cumulative total. To find the above-mentioned 20% of factors, the line starts from the 80% mark of the right vertical axis (cumulative percentage) dropped up to horizontal axis at the point of intersection with the cumulative curve. This 80% line diverted up to the horizontal axis separates the most influential factors (called vital few) on the left from the less significant factors on the right (called trivial many) [29].

We used What-if analysis/sensitivity analysis to identify the most influential GWP factors in each factory by determining the extent to which a change in a GWP parameter would affect the total GWP in every factory. To do so, one parameter in the model was changed by 5% at a time. For each parameter change the output was recorded, and illustrated using a Tornado plot (Fig. 2.7). The longer the bar in Tornado plot, the greater the variation or sensitivity. As we used a linear GWP model in this study, the change in the outcome becomes symmetric across the baseline axis.

Then, for identifying easily reducible factors and viable improvement options as stated in second objective, we conducted interviews with workers, factory officials, electrical superintendents, and engineers and referred to the literature.

2.3.4. Improvement Option Validation (Step 3)

In order to validate the improvement options identified in step 2, MFA, MFCA, and LCA were executed as in step 1 assuming that these options are in place. Initially, the options were validated individually and then, a scenario of which all options were applied, referred to as ’Combined scenario’, was developed and validated. A simple cost-benefit analysis was also conducted to clarify the payback period of Combined scenario. Furthermore, performances of the present and intended scenarios were compared using five of the Organization for Economic Co-operation and Development’s (OECD) sustainable manufacturing indicators (SMIs): water intensity (O1), energy intensity (O2), renewable proportion of energy (O3), GHG intensity (O4), and residuals intensity (O5). SMIs are internationally applicable common set of indicators that can measure environmental performances at the level of a plant or facility [53].

2.4. Results and Discussion

2.4.1. Quantification of Materials Involved (Step 1)

Summary of the inputs and outputs of material and energy for 1 MT of input rubber are given in Table 2.2. In addition, Fig. 2.3 illustrates how materials pass through the system of processing crepe rubber. On average, 3,176 kg of latex is required to get 1,000 kg rubber to the factory for processing to obtain 858 kg of processed crepe rubber at the end. Auxiliary materials that are attached to the final product have been limited to LDPE film used for packaging the highest grade of crepe rubber. Among operating materials, which are not bound into the final product, water had the highest share.

Table 2.2 Mean values with the Relative Standard Deviation of inputs/outputs of the materials involved in crepe rubber manufacturing system. Code LDPE refers to low-density polyethylene.

Input/output	Quantity
Input	
Raw materials	
Field latex [kg]	3,176 ± 12%
Auxilary materials	
Packaging material (LDPE film)[kg]	2.13 ± 38%
Operating materials/substances	
Sodium bisulfite [kg]	4.68 ± 7%
Formic acid [kg]	4.58 ± 12%
Bleaching agent [kg]	1.15 ± 5%
Water [kg]	55,627 ± 29%
Firewood [kg]	510 ± 41%
Electricity [kWh]	591 ± 17%
Output	
Main product (White crepe) [kg]	858 ± 2%
Secondary-product (Yellow Crepe) [kg]	103 ± 20%
Rubber loss [kg]	41 ± 20%
Wastewater [kg]	63,161 ± 21%
On-site emissions [kg]	768 ± 32%
Ash [kg]	7.65 ± 41%

Whilst water was the highest consuming component in operating materials, the variability of water use among factories was also high as shown by the RSD. Poor maintenance in all factories resulted in unexpected water system breakdowns and leakages causing such high level of variability. High level of water use together with the water in latex generated high amount of wastewater with an average of 63,161kg ± 21%

kg per 1 MT of rubber input. Due to mismanagements in chemical addition, quantities of formic acid used among the factories also showed a substantial variability. Even though the amount of packaging material (LDPE films) was quite small with an average use of 2.13 kg per 1MT of rubber inputs, its variability in terms of RSD was recorded as high as 38% due to the use of different grades in LDPE films. The highest variability in input materials was recorded in the firewood use. No proper standards in place for furnaces, radiators used in hot water circulation and drying tower would have resulted in such high variability. In energy use, electricity has also shown high level of variability (591 ± 17% kWh) and that could be attributed to the deficiencies in old machinery, lights and architectural designs of the factories.

Output of the final product, i.e., white crepe, was 85.8% from the rubber input and its variability remained at very low level with RSD of 2%. Nevertheless, output of yellow crepe which can be considered as a low grade product, was only about 10.3% from the rubber input but showed very high level variability among factories. Total value of white crepe and yellow crepe is rather conservative due to their high level of interconnectivity, i.e. any increase in white crepe fraction will decrease the yellow crepe fraction and vice versa. Therefore, a slight change in white crepe fraction will have a substantial effect on the amount of yellow crepe justifying the high level of RSD.

Fig. 2.4 illustrates the MFCA of the crepe rubber processing system. The largest material loss occurred during wet processing (QC1) which has contributed to a monetary loss of LKR 9,805 ± 11% per 1 MT of rubber input. Wet processing comprises steps involved in standardization, coagulation, maceration, diamond rolling, and smooth rolling as shown in Fig. 2.1. For QC1, materials losses are the operating materials (water and chemicals) that stream out of the system as non-product outputs (NPOs). Cost of material loss at this stage showed high level of variability. Any increase in NPOs can increase negative material cost and then, waste management cost due to the increased level of electricity used in wastewater treatment plants [N.B. In these plants, energy-intensive motors are used as aerators]. At QC1, negative material and waste management costs could be quantified as LKR 5,545 ± 29% and LKR 4,261 ± 19%, respectively. Apart from NPOs, raw material (rubber) losses were caused by the removal of dirt with rubber and in the cutting operation at QC3 and QC5. Therefore, at QC3 and QC5, negative material costs were LKR 3,795 ± 25% and LKR 5,324 ± 54%, respectively. Furthermore, at QC3 and QC5, negative system and energy costs were also observed. At QC3, negative system and energy costs were LKR 228 ± 71% and LKR 54 ± 68%, respectively, whereas they were LKR 279 ± 19% and LKR 82 ± 55% at QC5.

Fig. 2.5 illustrates the GWP breakdown by activity. Total GWP of the crepe rubber processing system was calculated as 279.3 ± 13% kg CO2e. In contrast, Kumara et al. [18] reported annual GHG emissions from crepe rubber processing as 2.08 MT CO2e/ha. If the GHG value of the present study is normalized to a unit of MT CO2e/ha per year considering that rubber plantations in Sri Lanka yearly yield 1.2 MT per hectare in average [54], GWP is to be recorded as 0.3 MT CO2e/ha per year. Exclusion of CO_2 emissions from firewood burning and GHG emissions bound with latex transportation to the factories could reason out such a deviation in GWP in our study. Firewood comes from rubber lands being replanted [6]; hence, such exclusion in the estimation of GWP could be justified. Out of all the activities, electricity generation was the main contributor, representing 89% of GWP. Firewood burning and formic acid use have moderately contributed, with about 5% and 4% respectively whilst rest of the activities showed negligible effect on total GWP.

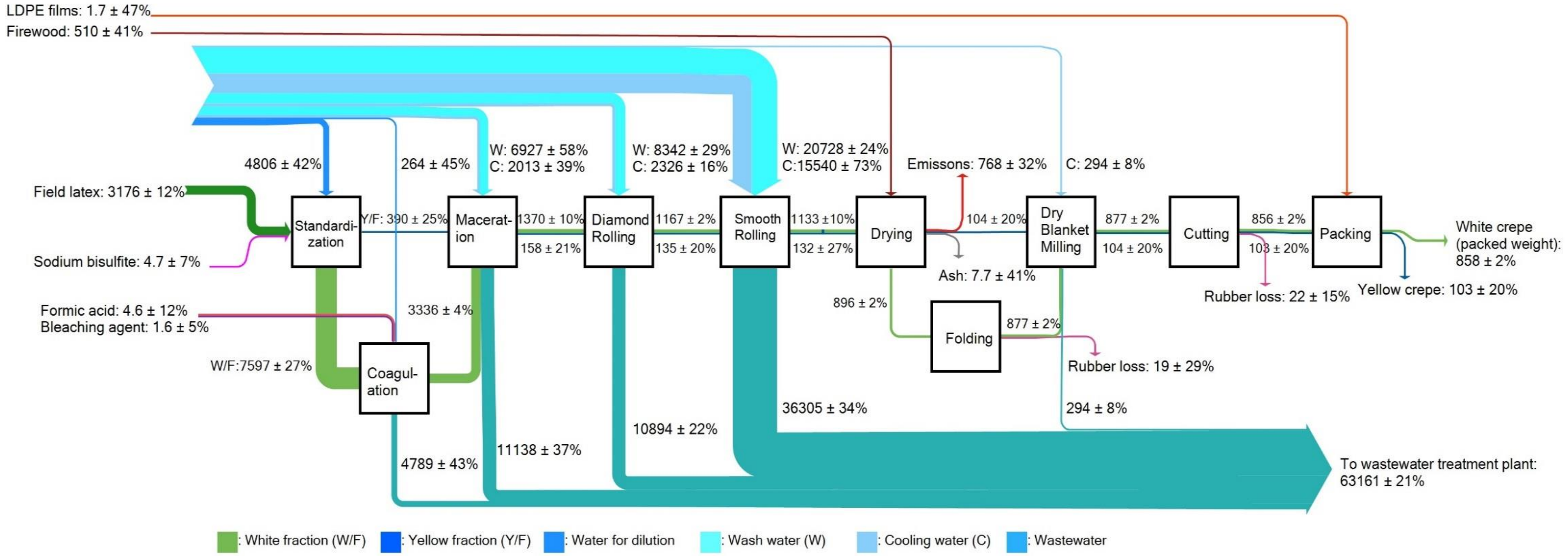

Fig. 2.3. Material Flow Analyses (MFA) of the crepe rubber manufacturing system. Mean values for all factories are given with Relative Standard Deviation in terms of kg/MT of rubber input. Code LDPE refers to low-density polyethylene.

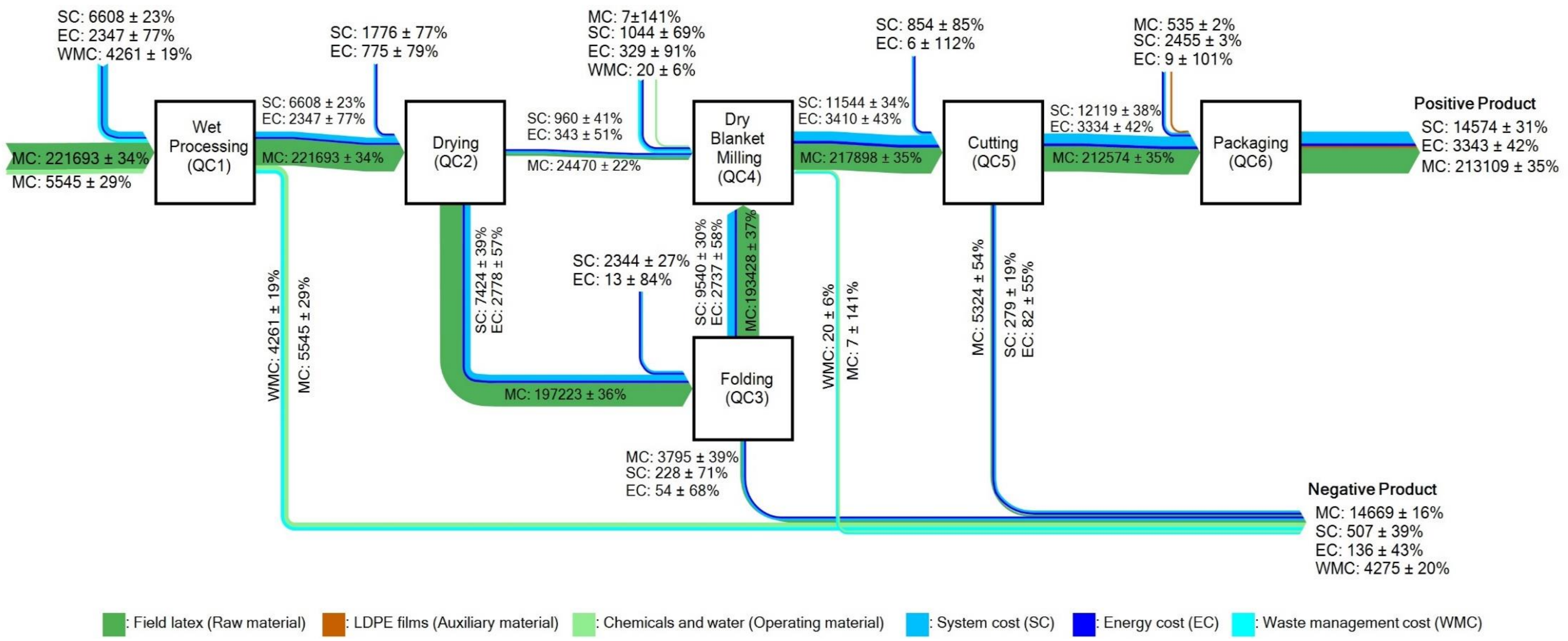

Fig. 2.4. Material Flow Cost Analyses (MFCA) of the crepe rubber manufacturing system. Mean values for all factories are given with Relative Standard Deviation in terms of LKR/MT of rubber input. Codes MC, SC, EC, WMC, and QC refer to material cost, system cost, electricity cost and waste management cost, and quantity center, respectively.

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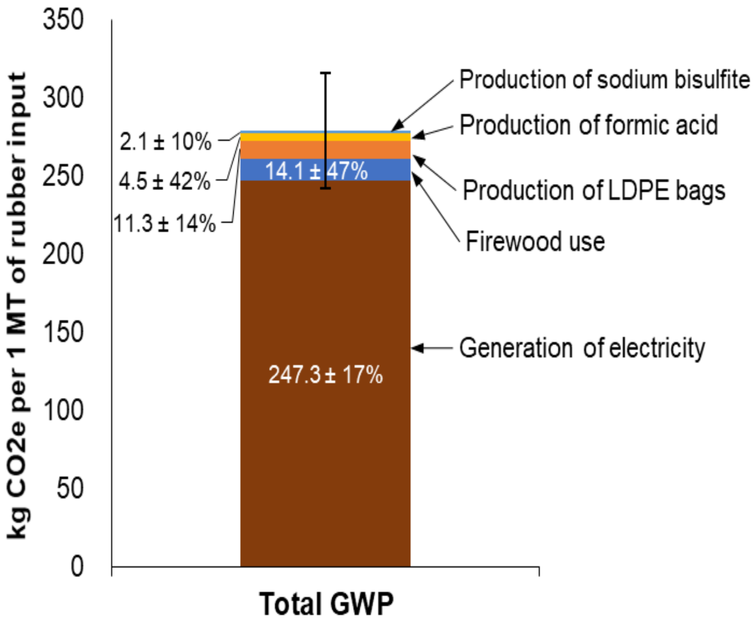

Fig. 2.5. Details of Global Warming Potential (GWP) of different components involved in the crepe rubber processing system. Mean values for all factories are given with relative standard deviation in terms of kg/MT of rubber input. Code LDPE refers to low-density polyethylene.

2.4.2. Impacts of the Proposal of Improvement Options (Step 2)

As illustrated in the Pareto diagram of factory A (Fig. 2.6), waste management cost at QC1, negative material cost at QC3 (associated with dirt), and negative material cost of NPO at QC1 could be considered as most influential since those factors cover the 80% of total negative costs [29]. Similar situation was observed in other two factories hence not presented. Discussions made with factory officers and managers have shown that both waste management and negative material costs at QC1 were the factors that could be reduced easily, whereas reduction in factors affecting rubber losses (e.g., negative material costs at QC3 and QC5) was not straight forward due to the influence of sub factors (e.g., handling errors, milling errors, dirty rollers, improper chemical addition, etc.). Considering the practicality in adoption, the following options could be proposed.

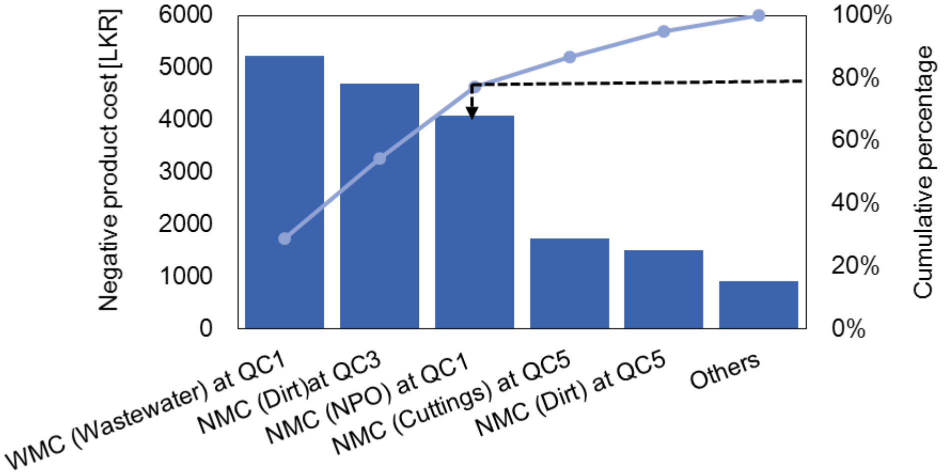

Fig.2.6. Pareto analysis for factory A. Codes, WMC (Wastewater) at QC1, NMC (Dirt) at QC1, NMC (NPO) at QC1, NMC (Cuttings) at QC5, and NMC (Dirt) at QC5 refer to waste management cost triggered by wastewater at quantity center 1, negative material cost of rubber with dirt at quantity center 3, negative material cost of non-product outputs at quantity center 1, negative material cost of rubber cuttings at quantity center 5, negative material cost of rubber with dirt at quantity center 5, respectively. Please refer to section 3.2.1 and Fig. 1 for quantity centers.

2.4.2.1. Reduction in Freshwater Use (Option-1)

Leaky pipes, joints, and valves are replaced with new fittings and a digital water meter is installed for the water supply to each roller. Furthermore, water flow rates (for washing and cooling water) at each roller are to be fixed. Since the wastewater generated by cooling was in a pure state and can easily be reused for cooling itself, each factory installs a water recirculation cooling system. Such a system has the ability to chill and recirculate the water wasted after machinery cooling at a constant rate. Relevant information on the most suitable water recirculation cooling system was gathered contacting a company specialized in such systems and considered in step 3.

2.4.2.2. Reduction in Chemical Use (Option-2)

In general, the chemicals added at coagulation depend on DRC, in other words, the amount of white fraction in the settling tank. Furthermore, the concentration of DRC in latex (%DRC) tends to vary with the external factors (e.g., genotype of the rubber tree, weather conditions, and extent of fractionation). However, in factories A, B, and D, chemicals were added with the assumption that %DRC in settling tanks was 90% of the initial DRC. Inaccuracy of this assumption resulted in wastages in chemical use. In factory C, chemicals were added after measuring %DRC with Metrolac (i.e., a hydrometer designed to measure %DRC of latex) and so, wastages were minimal. Hence, it is recommended to add chemicals after DRC measurements with Metrolac.

Tornado plot of the What-if analysis conducted on factory C shows that electricity use is most influential to global warming (Fig.2.7). Therefore, even a slight reduction in electricity will result in a considerable reduction in GWP. Furthermore, the situation was the same for the other factories.

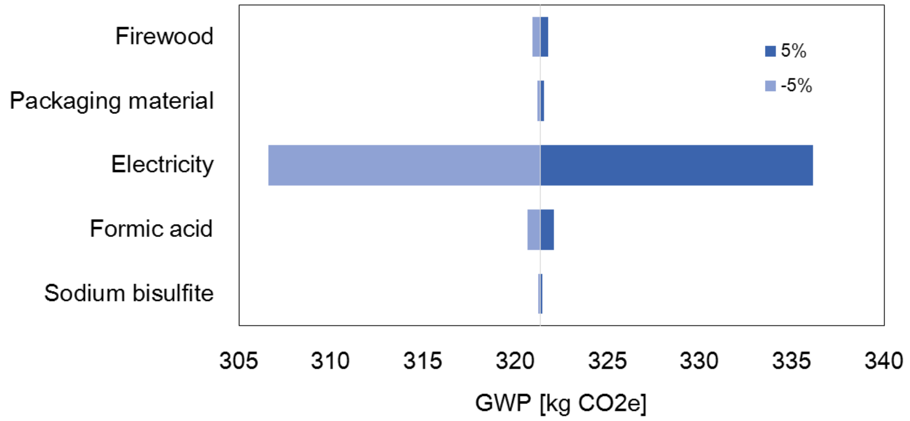

Fig. 2.7. Tornado plot of What-if analysis at mill C for key components associated with greenhouse gas emissions. Code GWP refer to global warming potential.

2.4.2.3. Reduction in Electricity (Option-3)

All factories replace old CFL and fluorescent lamps with LED lamps that deliver the same amount of light. Here, we assume that old fittings (holders, wires) are unchanged.

2.4.3. Validation of Improvement Options (Step 3)

The options proposed in step 3 were validated by re-executing MFA, MFCA, and LCA for each factory. Furthermore, simple payback period and relevant SMIs were calculated.

2.4.3.1. Reduction in Freshwater Use by Recirculation (Option-1)

This option could reduce water use of the crepe rubber processing system by an average of 32,064 kg and waste management cost at QC1 from LKR 4,261 (RSD 19%) to LKR 4,042 (RSD 11%) per 1 MT of rubber input (when factories A, C, and D are considered due to lack of data for MFCA and LCA in factory B). In addition, negative material cost per 1 MT rubber input at QC 1 could be reduced from LKR 14,668 (RSD 16%) to LKR 14,135 (RSD 15%). Altogether, the system`s total negative product cost had decreased by 3.6% per 1 MT of rubber input (i.e., LKR 19,585 (RSD 7%) to LKR 18,833 (RSD 12%)). Therefore, total manufacturing cost per 1 MT of rubber manufacturing dropped to LKR 249,860 (RSD 30%) from LKR 250,613 (RSD 30%). In addition to economic gains, Option-1 reduced the system`s GWP (per 1 MT rubber input) from 279.3 (RSD 13%) kg CO2e to 277.6 (RSD 24%) kg CO2e due to the reduction in electricity needed for water pumping and effluent treatment.

2.4.3.2. Reduction in Chemical Use (Option-2)

Even though formic acid and bleaching agent reductions projected by option-2 were negligible, it could reduce negative material cost per 1 MT of rubber input at QC 1 from LKR 5,544 (RSD 29%) to LKR 5,399 (RSD 27%). Along with that, total negative product cost was reduced from LKR 19,585 (RSD 7%) to LKR 19,440 (RSD 8%). However, the reduction in system`s GWP was marginal, i.e., 0.2 kg CO2e per 1 MT of rubber input.

2.4.3.3. Reduction in Electricity (Option-3)

Option-3 saved 3.4 kWh of electricity reducing the system`s GWP by an average of 1.5 kg CO2e per 1 MT of rubber input, i.e., from 279.3 (RSD 13%) kg CO2e to 277.9 (RSD 13%) kg CO2e. Effect of indirect reductions in some cost components (e.g., negative electricity cost, total electricity cost, total manufacturing cost) were found negligible.

2.4.3.4. Application of Option-1, -2, and -3 (Combined Scenario)

Option-1, -2, and -3 together reduced total negative product cost by 4.5% per 1 MT of rubber inputs (i.e., from LKR 19,585 (RSD 7%) to LKR 18,687 (RSD 12%)). However, the reduction of system's GWP was marginal with a reduction percentage of 1.1% per 1 MT of rubber input (i.e., 279.3 (RSD 13%) kg CO2e to 276.1 (RSD 24%) kg CO2e per 1 MT of rubber input). In this case, total manufacturing cost per 1 MT of rubber input decreased from LKR 250,613 (RSD 30%) to LKR 249,675 (RSD 30%).

Despite the average values presented above, improvements at individual factory level may have higher impacts than what observed. For instance, it was notable that factory C`s smooth rolling duration (SRD) varied considerably compared to that of the other factories due to not adjusting worn out rollers in regular intervals. Working duration of the water recirculation in cooling system solely depends on SRD; hence, reduction in factory C`s SRD results in additional benefits. It seems that SRD in factory C could easily be shortened by adjusting the roller weights. Therefore, if factory C reduces its SRD down to the median SRD of all factories, calculations highlight that total negative product cost and GWP decline further by 0.7 % and 3.4 % (i.e., to the values of 18,552 (RSD 11%) and 266.6 (RSD 19%) kg CO2e), respectively. The cost flow and GWP drop after all improvements (i.e., including SRD improvement in factory C) are illustrated in Fig. 2.8 and 9, respectively.

Extrapolation of values to one year period under the average production level of crepe rubber in factories shows that the combined scenario would result in 10,398 MT/year, 44.7 kg/year, and 11.3 MWh/year of water, chemical, and electricity savings, respectively. Also, the system saves 360,876 LKR/year of its costs and reduces GWP down to 109 MT CO2e/year from the initial value of 112 MT CO2e/ year. Meanwhile, the simple payback period was 2 ± 1 years. This result shows that the manufacturing system recovers the costs allocated for its improvements within 1 to 3 years.

Comparison of environmental performances of the combined to the baseline (initial) scenario is shown in Fig. 2.10. In addition, the mean indicator values for these scenarios are given in Table 2.3. Notable changes are visible in water use intensity (O1) and residuals intensity (O5), with the decline values of about 53% and 50%, respectively. This is due to the option-1 which has a significant potential to reduce total water intake and the residual by about 52% and 56% respectively. On the other hand, virtually no improvements were observed in energy intensity (O2) and renewable proportion of energy (O3), hence a marginal improvement in GHG intensity (O4) was recorded.

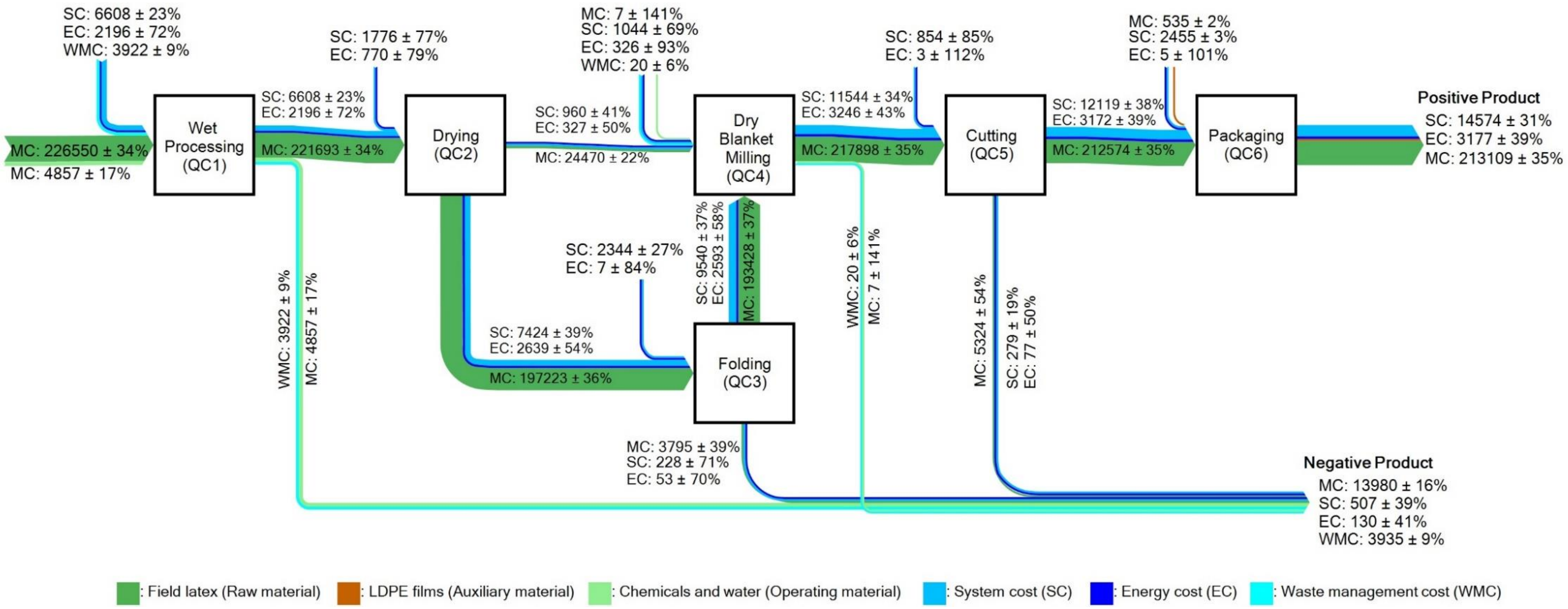

Fig. 2.8. Material Flow Cost Analyses (MFCA) under the combined scenario of crepe rubber manufacturing system. Mean values for all factories are given with Relative Standard Deviation in terms of LKR/MT of rubber input. Codes MC, SC, EC, WMC, and QC refer to material cost, system cost, electricity cost and waste management cost, and quantity center, respectively.

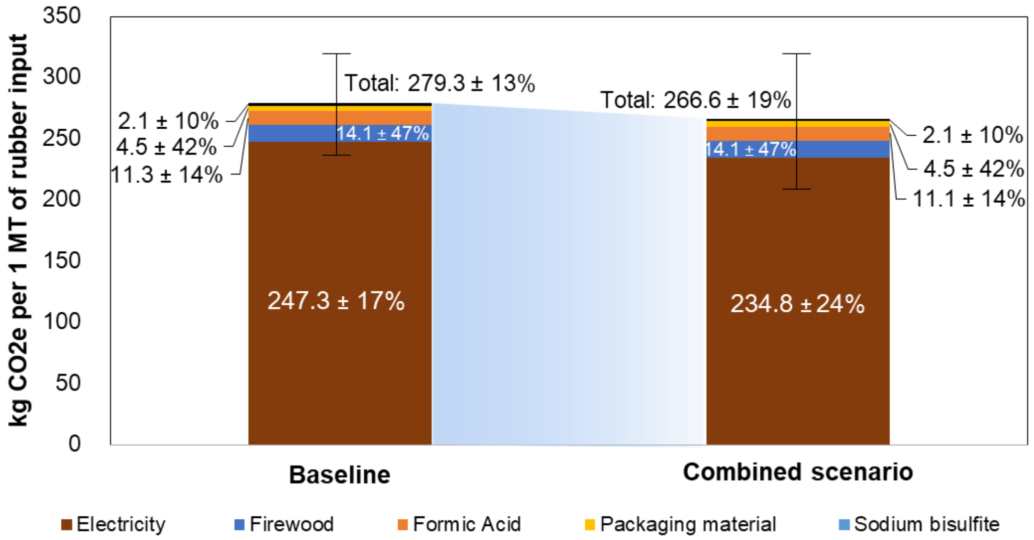

Fig. 2.9. Comparison of Global Warming Potential (GWP) of combined scenario with the baseline scenario (initial scenario)**.** Mean values for all factories are given with relative standard deviation in terms of kg/MT of rubber input.

Table 2.3 Indicator values (absolute value ± Relative Standard Deviation) for the crepe rubber processing system. Code descriptions and are given below.

Scenarios	O1 [m^3/MT*]	O2 [MJ/MT*]	O3 [%]	O4 [MTCO2e/MT*]	O5 [MT/MT*]
Baseline (initial)	64.26 ± 21%	9770.55 ± 34%	77.54 ± 13%	0.290 ± 29%	66.34 ± 21%
Combined scenario	30.10 ± 6%	9659.18 ± 32%	78.21 ± 14%	0.277 ± 18%	32.89 ± 4%

MT*: metric ton of product (crepe rubber), O1: water intensity, O2: energy intensity, O3: renewable proportion of energy, O4: GHG intensity, O5: residuals intensity

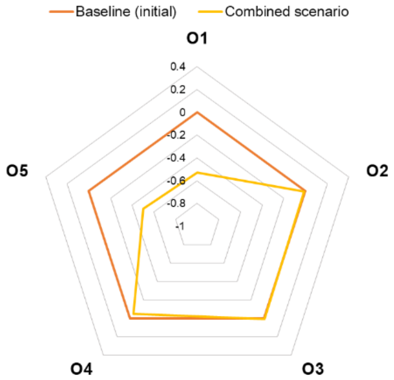

Fig. 2.10. Comparison of the environmental performances in the combined scenario to those in the baseline. The initial scenario is located at 0 and indicated in orange, whereas a yellow line indicates the combined scenario. Codes, O1, O2, O3, O4, and O5 refer to water intensity, energy intensity, renewable proportion of energy, GHG intensity, residuals intensity, respectively.

Overall, the results demonstrated that economic and environmental performances in crepe rubber manufacturing can be increased considerably by reducing the most influential loss costs and GWP factors. This results in noteworthy cost reduction and moderate GWP savings and in particular, the use of fresh water and formic acid and bleaching agent could also be reduced.

Quantity of fresh water use was not valued in this study due to its free abundance in the area where factories located. Due to high demand for water, rubber processing factories had been built close to free water sources in past. However, in future, it will not be the case and water has to be valued in Sri Lanka and elsewhere. Under such circumstances, any measure on water saving would have a greater effect on the profits than what observed in this study. Moreover, reduction in fresh water use may preserve adjacent water resources and reduce the burden on wastewater treatment plants through wastewater reduction. In particular, possibilities of overflows at treatment plants during high crop seasons and water scarcity during droughts will be avoided. Reduction of water use may cut off additional GHG emissions incurred due to fuel combustion of the bowsers carrying fresh water to the factories during droughts.

Less chemical use means less potential for toxicity in wastewater; hence use of right amounts of chemicals in crepe rubber processing minimizes the chemical odor and the burden on treatment plants. Despite the reduction in electricity under option 3 is marginal at the level of 1 MT of rubber input, the extrapolated GWP cutbacks were noteworthy at 384 kg CO2e per year. Though have been neglected by factories, SRD was identified to be an important factor that could reduce GWP by minimizing the electricity consumption of itself and water recirculation system. In addition to GWP cutbacks, any reduction of electricity use would create less demand for primary fuels such as coal and petroleum (N.B. 47% of electricity in Sri Lanka generated via petroleum and coal [55]). This would minimize the environmental contamination from mining operations, drilling leaks, and explosions inherited with primary fuel extraction.

Although the present study was done with crepe rubber manufacture, the key findings could be applied in other types of dry rubber processing in large scale since similar machineries are used in all cases. Depending on the market price, the factories used in this study produces RSS with limited use of machineries. Sole crepe (another type of crepe rubber produced for the soles of winter shoes) could also be produced in the same factories with some modifications in the process. With the benefits of improvement options proposed in this study, raw rubber industry could be more competitive in the market achieving more profits, increased sales and reduced levels of toxins released into the atmosphere. Despite the environmental friendliness in rubber cultivation, raw rubber processing is generally considered by public as a polluting process due to the problems associated with waste management [12]. Therefore, the improvements proposed herein could build a positive social image to the NR industry though this study did not address the social aspect of crepe rubber processing. Further, the proposed move may widen the market share attracting a new set of customers who prefer sustainably processed crepe rubber to conventionally manufactured ones. In addition, building the industry's reputation may boost workers` morale by fostering a culture of teamwork and continuous improvement [56]. If such situation attracts more youth to work at NR factories, the labor shortage in this industry could be addressed [57].

In a state which the literature is merely available on wastewater treatment plants or some other partial analyses in economic or environmental aspect of the crepe rubber manufacture, this study provides an evidence for the importance and validity of using an integrated model in combination with MFA, MFCA, LCA, Pareto, what-if and cost benefit analyses in restoring the issues in crepe rubber manufacture. Pinpointing unprecedented economic as well as environmental hotspots and foreseeing degree of improvement had been noteworthy features of this integrated model. Furthermore, illustration techniques such as Sankey diagrams and spider charts of SMIs had provided a stern basis to visualize the situation before/after improvements and identify the segments where further improvements were necessary. Therefore, factories may use our illustration techniques in their Cooperate Social Sustainability (CSR) reports and other demonstrations in view of improving the quality of reporting and rendering a clear insight into their efforts in sustainability. SMI charts can also be used to monitor the progress made over time. As the improvement process goes on, number of SMIs can be increased (i.e., from 5 to a maximum number of 18 [53]) in order to get a clearer overview of the progress.

In addition to the reduction options suggested in this study, there are some other options for further improvements. Reutilization of treated water and recirculation of a smooth roller`s wastewater [25] are some of the options for further reducing water use. The first concept, reutilization of wastewater, had been tested for a block rubber factory and proven to be immensely effective in terms of environmental and financial attributes [58]. Therefore, future research should test the applicability of this concept to crepe rubber factories. Replacing old machines with new ones, installing new motors and power factor corrections, biogas cogeneration and installing solar panels are some potential measures to reduce energy use. In a situation which Sri Lankan government is trying to promote solar electricity across industries and households via a project called 'battle for solar energy' [59], we believe that an option like solar panels would be the most appropriate in this regard. Biogas cogeneration can also play a pivotal role in reducing energy demand, as it can turn the biogas from anaerobic digester of wastewater treatment plant into heat energy or electricity as per factory`s preference. Just one step in energy conversion, the former is less costly and convenient hence preferred over the latter. Biogas can be utilized as a heat source for drying tower in the factory. In a scenario of having solar panels, the amount of electricity generated would vary with the weather pattern; however, it may also correlate with rubber latex production due to the fact that both processes (i.e. electricity and latex generation) are driven by the same energy source and affected by rains. For instance, less electricity and latex yields are recorded during rainy periods. Despite such benefits in solar energy and then use of biogas, the options required less investments were the focus of the study; hence, future work may give prior attention to the options discussed herein.

To us, if more attention is paid on reducing the factors which are not straightforward (e.g., negative material costs at QC3 and QC5), negative material, system and energy costs of crepe manufacture can notably be reduced. Therefore, total negative product cost will also be reduced significantly. Since negative material cost at QC3 and QC5 comprise several sub-factors (e.g., handling errors, milling errors, dirty rollers, improper chemical addition, etc.), distinguishing significant sub-factors of these becomes necessary. In such a case, cause-effect diagrams (fishbone or Ishikawa diagram) can be used.

Although some factories (e.g., factory C) have already made promising efforts towards sustainable manufacturing, barriers to such still exist. Field interviews revealed that limited expertise in sustainable manufacturing and practices, lack of in-plant expertise, priorities given to short-term profits and market share, and higher initial capital costs are some of these barriers. Furthermore, factories may refrain from sharing successful sustainable manufacturing practices with others to be more competitive in the market. Therefore, in demolishing these barriers, training and awareness programs on sustainable manufacturing and practices, process analysis techniques and tools will be useful. 5S training can also be effective in this regard because the 5S concept provides a methodical way to turn a workplace into a safer, ergonomic and more efficient environment [12]. Moreover, responsible authorities may encourage factory managements to initialize a sustainable manufacturing culture at respective premises by provisioning financial assistance (e.g., subsidies and tax credits). Creating a system that shares successful sustainable manufacturing stories may accelerate the whole transformation process of crepe rubber manufacture into a sustainable one.

2.5. Conclusions

The study reveal that present status of crepe rubber manufacturing in Sri Lanka generates 63,161 (RSD 21%) kg of wastewater, 41 (RSD 20%) kg of rubber waste, 768 (RSD 32%) kg of on-site emissions, and 7.65 (RSD 41%) of ash per 1 MT of rubber input, showing inefficient use of water, chemicals, and energy. This has resulted in economic loss of LKR 19,585 (RSD 7%) and GWP impact of 279.3 (RSD 13%) kg CO2e. Among the options for improvements, reduction in fresh water, chemicals and electricity use (i.e., Option-1, -2, and -3) could lead to reductions of 32,064 kg of water, a negligible amount of chemicals, and 7.5 kWh of electricity per 1 MT of rubber inputs, respectively. These reductions could save 4.5% of the cost and reduced 1.1 % of GWP. At individual case, reducing SRD in factory C resulted in additional cost savings and GWP reductions further minimizing the said values up to 5.3% and 4.3% respectively.

2.5.1. General Implications

Improvement options proposed in this study for crepe rubber processing can result in more profits, an increase in sales, and a reduction in toxins that are released into the atmosphere. Furthermore, preservation of water resources, ecosystem conservation, uplifted corporate image, and improvement in the quality of life can be anticipated. Altogether, such improvements will boost workers' morale and lay a foundation for a culture of teamwork and continuous improvement. Therefore, apart from the direct environmental and economic gains, the indirect social gains are also foreseeable.

Despite some hindrances for sustainable manufacturing, application of this MFA-based methodology can serve as a tool for analyzing the degree of performances in regular intervals, not only in crepe rubber processing sector itself, but also in any other manufacturing sectors rooted in developing countries. Outcomes at each turn can be utilized for benchmarking and/or improving or predicating the economic and environmental performances in factory or industry in times to come.

2.5.2. Managerial Implications

Being most feasible, the improvement options identified in this study (option -1, -2, and -3) are to be tried out by the managers of the respective factories. Potential improvements shown here could be taken into account when deciding the priority options in the adoption process. Other options stressed in the study (e.g., reutilization of treated water, installing solar panels, biogas cogeneration) may also be implemented thereafter. Charts of SMIs can be used in order to overview the progress.

Managers should also pay attention on a less reducible factor such as negative material cost at QC3 and try to find roots of such a waste. Cause-effect model can be used for such process. Though not attempted properly, interview with managers revealed that the waste can mainly be eliminated through proper maintenance practices such as regular cleaning of rollers and floors, proper filtration of field latex at the standardization stage, accurate chemical additions, and reducing milling errors. Hence, regular inspections should be given by factory officials in order to ascertain that their workers follow these practices properly.

Policy decisions are to be taken to implement the proposals made in this study for improvements in crepe rubber manufacture and to eliminate the barriers in the implementation. Awareness programs to educate factory officials on the techniques and tools given in this study and building up model factories will become the foundation of the whole transforming process of the current manufacturing process into a sustainable one. Provision of financial support and creating system that shares successful sustainable manufacturing stories can boost the ultimate target of achieving sustainability.

2.5.3. Limitation and Future Research

This study shed light on the main aspects of "sustainable manufacturing"; which can be defined as "developing and establishing energy efficient, non-polluting, economically viable processes for manufacturing of products" [60]. Therefore, this study puts hands only on economic and environmental dimensions of crepe rubber production. Although the results of this research entail indirect social implications, however, not directly addressing the social dimension can be given as a limitation of this study. To fill this gap, future research may consider integrating a social life cycle assessment (SLCA) into the present approach. They may also include emissions from bleaching agent manufacture and wastewater treatment when calculating GWP impact. In addition to the GWP impact index, other impact categories in LCA (e.g., ozone layer depletion, human toxicity, eutrophication, etc.) are also to be added on. Though rubber plantations have been identified as carbon negative (due to carbon fixation) by previous studies, their economic, social and other environmental impacts remain unidentified. To fill this gap, future work may modify the present approach in view of extending it to rubber plantations. As per the suggestions made so far, undealt but high impact options (e.g. solar electricity) in raw rubber manufacturing should be tried first. In addition to crepe rubber, the present approach or its modified version should be applied to the other major raw rubber products (e.g., concentrated latex, ribbed smoked sheets, etc.). We believe that such attempts may unveil interesting and useful facts that this sector can immensely benefit from.

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CHAPTER 3 Financial and Environmental Sustainability in Terms of Process Analysis and Decision-Making Tools: A Study of Ribbed Smoked Sheet Manufacture

3.1 Background

Sri Lanka is the eighth largest natural rubber producer in the world and accounts for ca.1.2% of natural rubber produced worldwide [1]. Being the second largest crop-based industry in island, natural rubber industry has been a key contributor to Sri Lankan economy in terms of foreign exchange earnings and employement generation. For instance, 88.57 MT of natural rubber had been produced in 2015 and 10.37 MT of which had been exported with a value of USD 22.13 million [2]. Moreover, over 300,000 of employement opportunities have been recorded to have generated by this sector to Sri Lankans across various professions and walks of life [3]. Natural rubber is used to produce value added rubbber products like tyres, tubes, footwear, condoms, surgical gloves, etc. which are indespensible for humans. Ribbed smoked sheet(s) (RSS) is a type of natural rubber which dominates the natural rubber manufacture in Sri Lanka and elsewhere. More than 50% of natural rubber produced in Sri Lanka is in the form of RSS [4]. RSS is used as a raw material for tires, tubes, hoses and footwear at value addition. RSS manufacture in Sri Lanka is mostly done in small scale within the farmland.

RSS manufacture is a labor-, energy-, and material-intensive process; requires substantial amounts of thermal energy, fresh water, and chemicals at different stages of manufacture [5]. Therefore, RSS manufacture would have been confronted with high cost of production, low cost efficiency and various environmental impacts (e.g., water pollution, greenhouse gas (GHG) emissions., etc)[1][6][7][8].

Several studies have been conducted to scutinize above issues. Peiris[6] and Fagbemi et al. [9] outlined number of cleaner production measures to uplift the profitability and productivity with lesser environmental load in RSS manufacture. Rathnayake[10] reviewed an energy efficient smokehouse to smoke-dry RSS in a day to save cost of firewood and labor. In view of quantifying GHG emissions associated with RSS manufacture in Thailand, a life cycle assessment has been performed by Jawjit et al. [11]. Observing that firewood use as a key determinant affecting GHG emissions, Jawjit et al. [11] proposed various measures to uplift the efficiency of smokehouses to use less firewood. Same method has been follwed by Wijaya et al.[12] to quantify GHG emissions associated with RSS manufacture in Indonesia. Meanwhile, Musikavong[13] attempted quantifying water scarcity footprint of RSS manufacture in Thailand. A device called electrostatic precipitator has been introduced in Tekasakul et al.[14] and Tekasakul et al.[7] to minimize smoke particles inside RSS factories.

No previous studies have ever considered economic and environmental aspects of entire RSS manufacturing process as a whole. Instead, they have been confined to several partial analyses scrutinizing an issue or a set of issues belonging to economic or environmental aspect of RSS manufacture. Therefore, identification of real issues or hotspots in RSS manufacture would have been failed. None of the studies foresee the benefits of improvement options in quantifiable terms. Hence, this study aims at addressing such lacunas in view of developing RSS manufacture to be more cost-efficient and environmentally friendly.

3.2 RSS Manufacture

As mentioned in introduction, RSS manufacture in Sri Lanka is mostly done by smallholders. As shown in Fig. 3.1, rubber trees are tapped and man-handled to the factories. As soon as latex reaches the factory, latex is coagulated by adding water and formic acid after putting it across several flat pans. Once the coagulam formed, it is taken for milling. Two hand operated rollers,i.e., smooth and grooved rollers, are used for this purpose. Coagulum is passed two to three times through smooth roller before sending it once through grooved roller. Milled sheets are then rinsed and draped in a shade for dripping prior to smoke-drying. Smoke-drying is done by hanging sheets at a smokehouse and keeping them there for three to five days. The dried sheets are finally weighted and transported to regional retailing centers.

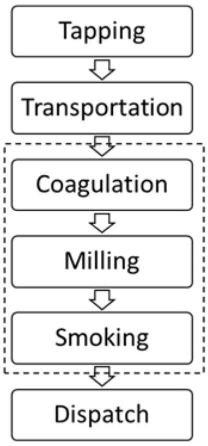

Fig. 3.1. Ribbed smoked sheet manufacture in Sri Lanka. Perforated line depicts the system boundary of the study.

3.3 Materials and Methods

3.3.1 Goal Definition

A three-stepped method has been deployed as follows: step-1) quantification of material flows and waste, monetary loss, and GHG emissions using material flow analysis (MFA), material flow cost accounting (MFCA) and life cycle assessment (LCA) respectively, step-2) Identification of key drivers of monetary loss and GHG emissions and developing improvement options using Pareto and What-if analyses, field interviews and literature; and step-3) Benefit validation via repetition of step-1.

3.3.2 Step-1

3.3.2.1 System Definition

This study entails all activities carried out in small scale RSS factories in Sri Lanka (please refer to Fig. 3.1). External activity such as formic acid production has also been considered for LCA herein.

3.3.2.2 Functional Unit

Production of 1 MT of RSS was considered as the functional unit of the study.

3.3.2.3 Data Collection

Data was collected by investigating three RSS factories (factory A, B, and C) belonging to rubber smallholders in Sri Lanka. They were scattered across three major rubber producing districts of Kegalle, Kurunegala, and Gampaha. All factroies were visited in person to collect required data. Dry rubber contents of field latex and throughputs, quantities of acid and water were measured on-site. Rubberwood required as firewood for smoke-drying was known by interviewing workers and owners. Lab experiment at Rubber Reaserch Institute of Sri Lanka was carried out for knowing ash content of rubber. Required emission factors for LCA were extracted referring to literature.

3.3.2.4 Material Flow Analysis

MFA is a systematic assessment of the flows and stocks of material within a system defined in a space and time [15]. MFA is used herein to visualize all material inflows, thoroughputs and outflows in RSS manufacture and to achieve an input-output balance.

Material flow for each factory was prepared using STAN 2.5 software [16] and finally combined to get a common material flow representing RSS manufacture in Sri Lanka. Values in material flow were indicated using mean ± standard error (SE). For the sake of clarity, material flow diagram herein was created using e!sankey sofware [17].

3.3.2.5 Material Flow Cost Accounting

MFCA is tool of having both environmental management accounting and cost reduction abilities, which surpasses traditional management accounting [18]. It allocates material, system, and energy costs into postive and negative product costs based on material flows at each quantity center (QC), i.e., unit process. However, waste management costs are soley allocated to negative product costs. Here, positive and negative product costs are the costs that are allocated to product and wastes, respectively [19]. Moreover, MFCA considers three types of materials [20]: raw, auxiliary and operating materials. Raw materials are materials that create final product. Auxiliary materials are the materials that end up in final product. Operating materials are essential for producing final product but always end up as non-product outputs, i.e., waste or emissions.

MFCA model of each factory was bulit on excel spreadsheets. Then all models were combined to get a common MFCA model which signifies RSS manufacture in Sri Lanka. Values in this model were indicated using mean ± SE. Sri Lankan rupees (LKR) was used as the unit for MFCA; LKR 1 = USD 0.0062. For clarity, e! Sankey software [17] was used to create common MFCA model in Fig. 3.3.

3.3.2.6 Life Cycle Assessment

LCA is a tool which measures environmental impacts of a product`s life cycle, i,e., from raw material extraction to diposal or recycling [21]. However, conducting an in-plant assessment has been the focus of LCA herein. Due to lack of data on emission factors, LCA herein has been confined to measuring global warming potential (GWP) impact incurred by GHGs. GWP impact model mentioned in Jawjit et al.[11] was used in this regard. In some cases where an emission factor was found in kg CO2e per unit, that was multiplied by level of actitvity to calculate GWP. Required emission factors were extracted from literature and are as follows: firewood use [11]; CO_2:110 kg/TJ, CH_4: 30 kg/TJ, N_2O: 4 kg/TJ; and formic acid [22]: 2.51 kgCO2e/kg. Since firewood came from the rubber trees which had been replanted, CO_2 emissions from firewood burning were not included in GWP impact. GWP impact per actitvity and total GWP were calculated for each factory and then combined to get common GWP impact values in mean ± SE representing RSS manufacture in Sri Lanka.

3.3.3 Step-2

Step-2 has two objectives: 1) Identifying key drivers of GWP impacts; and 2) Proposing applicable improvement options. For first objective, What-if analysis [23] was deployed to assesses the impact that one parameter in a model would incur on that model when it changes. Only one parameter is changed at each iteration while the changes are recorded and ultimately presented as a tornado plot (see Fig.3.5). The longer the bar, the greater the impact that a parameter have on model.

Second objective was achieved by interviewing factory owners and referring to literature.

3.3.4 Step-3

Objective of this step is to evaluate financial and environmental benefits of the proposed options. MFA,MFCA and LCA were re-executed in this regard. In order to compare the performances of options against that of current situation, changes in five Organisation for Economic Co-operation and Development`s sustainable manufacturing indicators (SMIs)[24] ((SMIs; water intensity (O1), energy intensity (O2), renewable proportion of energy (O3), GHG intensity (O4), and residual intensity (O5)) were examined.

3.4 Results and Discussion

3.4.1 Results of Step-1

As shown in Fig.3.2, manufacture of 1 MT RSS requires 2,764 ± 210 kg of field latex, 449 ± 46 kg of formic solution and 4,490 ± 1,532 kg of water. Not following industrial standards seems to have caused high uncertainties in the use of operating materials, i.e., formic acid and water. Firewood had been the only energy source for RSS manufacture and was used to generate heat for smoke-drying process. Average use of firewood was recorded as 767 kg per 1 MT of rubber input with a SE of 83. This amount provides 12,330 ± 1,334 MJ of thermal energy on the basis of 16.1 MJ per kg of firewood [25]. No wastewater treatment plants were installed at factories; hence, no treatment was given to wastewater prior to discharging.

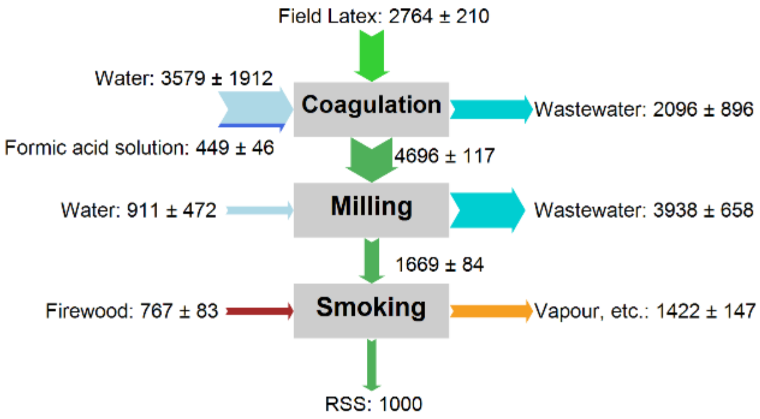

Fig. 3.2. Material flow analysis of ribbed smoked sheet manufacture (RSS) per 1 MT of RSS. All values are denoted as mean ± standard error in kg per 1 MT of RSS.

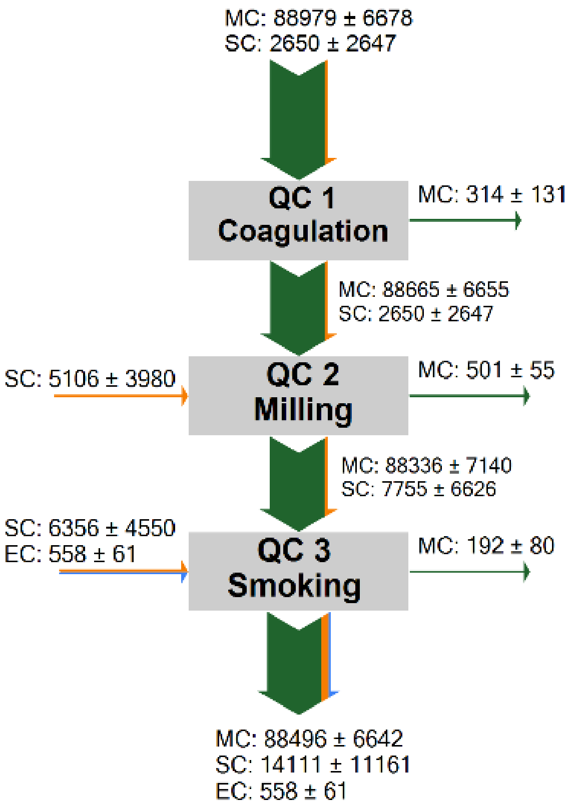

Fig. 3.3. Material flow cost accounting of ribbed smoked sheet manufacture (RSS) per 1 MT of RSS. Codes QC, MC, SC and EC refer to quantity center, material cost (in green), system cost (in orange), and energy cost (in light blue), respectively. All values are denoted as mean ± standard error in kg per 1 MT of RSS.

MFCA of RSS manufacture is illustrated in Fig.3.3 where all QCs incur negative material costs. This happens because formic acid acts as an operating material, in other words, it streams out at each QC as a non-product output. Meanwhile, no rubber losses were identified; hence, no negative electricity and system costs were evident. Total negative product cost of the system was recorded as LKR 1007 ± 42, reflecting ca. 1% of total input cost. This affirms that monetary loss of RSS manufacture is very less hence in a state which can be neglected.

As per LCA, GWP impact of RSS manufacture was found to be as low as 38.0 ± 2.1 kg CO2e. As shown in Fig.3.4, there were only two activities contributing to GWP impact in RSS processing; firewood and formic acid use. Of them, firewood use is the largest contributor to GWP impact accounting for ca. 63% of total GWP. In addition, formic acid use notably adds 14.0 ± 0.6 kg CO2e to total GWP impact in processing of 1 MT of rubber.

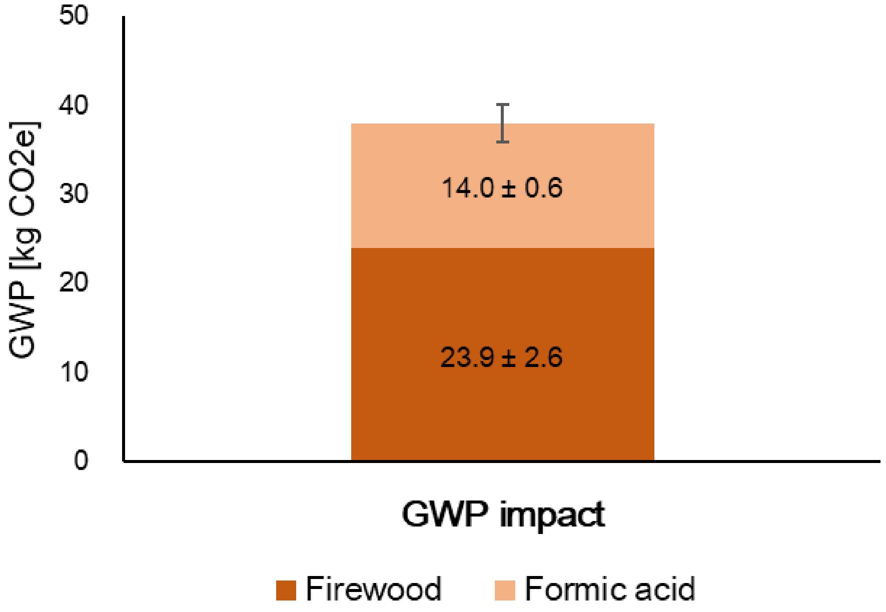

Fig. 3.4. Global warming potential (GWP) of ribbed smoked sheet manufacture (RSS) per 1 MT of RSS. All values are denoted as mean ± standard error in kg CO2e per 1 MT of RSS.

4.4.2 Results of Step-2

As per results of step-1, it appeared that monetary loss in RSS manufacture was negligible. Therefore, identifying key drivers affecting GWP impact was focused. What-if analyses performed on factory A, B and C highlighted that firewood use had been the most influential on GWP impact (Please refer to Fig. 3.5 for tornado plot of factory B). As mentioned in section 3.3.2.6, GWP herein excludes CO_2 emissions as firewood becomes a regenerated material.

Factory A was using an efficient smokehouse that could complete smoke-drying in a day. This smokehouse was called single-day smoke (SS) dryer [10]; hence, factory A consumed far less amount of firewood than other two factories did. Therefore, we propose factory B and C to install this SS dryer as an improvement option to reduce GWP impact.

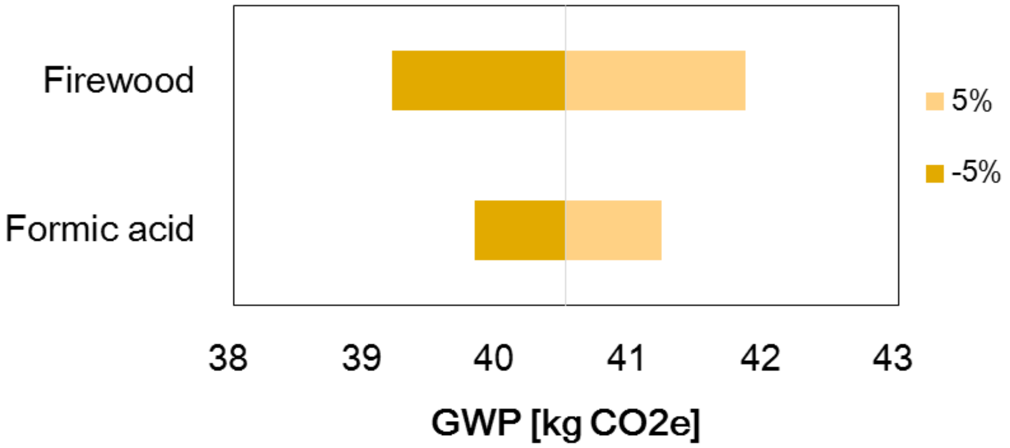

Fig. 3.5. Tornado plot of What-if analysis. GWP refers to global warming potential.

3.4.3 Results of Step-3

The main concern over applying SS dryer had been reducing GWP impact. As per results, GWP attributed to firewood combustion had reduced to 18.7 kg CO2e from 23.9 ± 2.6 kg CO2e per 1 MT of RSS; hence, total GWP per 1 MT of RSS had decreased to 32.7 ± 0.6 kg CO2e from 38.0 ± 2.1 kg CO2e. Though no change could be observed in negative product cost, overall manufacturing cost had slightly been reduced by 0.1% per 1 MT of RSS (from LKR 104004 ± 6336 to LKR 103883 ± 6386).

Among the potential changes in SMIs after installing SS dryer to factory B and C, the largest variation can be observed in O4 (GHG intensity) due to the reduced GWP impact (Fig. 3.6). Application of SS dryer has reduced firewood use in manufacture by 30%; hence, O2 (energy intensity) has also decreased. However, the rest of the indicators showed no significant changes.

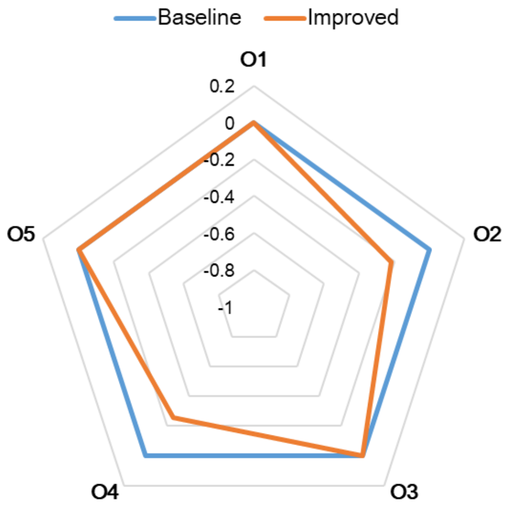

Fig. 3.6. Average change in sustainable manufacturing indicators for current situation (baseline) and improved situation of ribbed smoked sheet manufacture (RSS) per 1 MT of RSS. O1, O2, O3, O4 and O5 refer to water intensity, energy intensity, and renewable proportion of energy, GHG intensity, and residual intensity.

Overall, SS dryer had been a useful option for reducing not only GWP impact but also cost of manufacture. Moreover, additional benefits such as consuming low space in factory, and low health risks are foreseeable [10]. During the field visits, we observed that workers in factory B and C were excessively exposed to wood smoke as they entered smokehouses for firing and removing dried RSS. This is health-threatening [7]. Since SS dryer can be operated from outside, health risks are minimal.

Virtually, no studies on financial aspects in RSS manufacture are found; however, several studies have reported on GWP impact of RSS manufacture. GWP impact of Thai RSS manufacture had been recorded 40 kg CO2e [11] whereas that in Indonesia was 139 kg CO2e [12]. Both GWP impacts remain larger than GWP impact (i.e., 38 kg CO2e) recorded in this study for Sri Lanka. Scale of manufacture can be a major factor for this difference as both Thai and Indonesian GWP impacts were based on small and medium-sized factories. These factories used both electricity and firewood for their manufacture. GWP impact incurred by transportation has also been regarded in calculating above GWP impacts.

The method used herein had been very useful in identifying monetary loss, GWP impact and degree of improvement. If repeated after applying improvement options, this method may reveal a new set of issues at each repetition. Owners may try to address such issues when required to gain profits and environmental benefits. Progress made overtime can be analyzed using tools such as SMIs and illustration techniques introduced herein.

Apart from SS dryer, solar based dryers [26] may eliminate firewood consumption to have less GWP impact for RSS manufacture. Following industry`s standards can reduce formic acid consumption to have less monetary losses and GWP impact. This would also lower the toxicity in wastewater. Wastewater discharged during RSS manufacture had been a problem as it is given no prior treatment [8]. Therefore, installing small scale wastewater treatment plants may be considered by owners.

However, barriers to sustainability of RSS manufacture still exist; limited expertise in sustainable manufacturing or cleaner production tools and techniques, prioritizing profits and higher capital costs are some of them. Therefore, regular workshops on sustainable manufacturing and government subsidies provided for one who tries to initialize cleaner production are pivotal in addressing the said barriers.

Not assessing social impacts of RSS manufacture is a major lacuna in the method herein. Therefore, inclusion of a tool such as social life cycle assessment may be considered by future research. Evaluation of financial feasibility of SS dryer or any other improvement options is another component of importance. Adoption of discounted cash flow analyses with prominent financial indices such as net present value, internal rate of return and discounted payback period can be considered in this regard.

3.5 Conclusions

Current RSS manufacture in Sri Lanka incurs LKR 1007 ± 42 of monetary losses and 38.0 ± 2.1 kg CO2e of GWP impact per 1 MT of RSS. Identifying key monetary loss factors was skipped as monetary losses remained ca. 1% of total manufacturing cost. Firewood use was observed as a key factor affecting GWP impact. Therefore, SS dryer in factory A was proposed for factory B and C, as an improvement option for reducing GWP impact. SS dryer could reduce firewood use by 30%, resulting 0.1% and 14% reductions in cost of manufacture and GWP impact, respectively. This study has taken an initial step to improve RSS manufacture and stressed the importance of combining process analysis and decision-making techniques and tools. Therefore, future research may develop the method herein for further improvements in RSS manufacture.

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CHAPTER 4 Further Improving Financial and Environmental Sustainability in Terms of Process Analysis and Decision-Making Tools Integrated in a Method Based on Continuous Improvement Concept: A Case Study with a Crepe Rubber Factory in Sri Lanka

4.1. Introduction

Rubber products are indispensable in present day context; and on average, each person consumes ca. 3.5 kg of rubber per year [1][2]. Being renewable and having some unique qualities, natural rubber supply plays a decisive role in rubber product manufacture. In rubber product manufacturing, each product has specific needs in raw rubber use; hence, required standards in natural rubber are to be maintained in raw rubber processing assuring acceptable market price. Production of natural rubber is mostly in the tropical Asian region. In Sri Lanka, the rubber sector ranked as the third largest foreign exchange earner with its exports contributing 122,074 million rupees (824 million USD) to the foreign exchange revenue in 2014 [3][4]. Furthermore, this sector has been a source of 300,000 direct and indirect job opportunities to Sri Lankans [3]. Once latex is collected from rubber trees, it is processed into primary products, referred to as raw rubber, that are then utilized in different manufacturing industries to be reprocessed into rubber products. In Sri Lanka, raw rubber is produced mainly in the form of ribbed smoked sheets (RSS), concentrated latex (CL), and crepe; which have been the principal raw material of many rubber products such as pneumatic and solid tires, some other components in vehicles, condoms, hoses and, pharmaceutical and surgical items [5][6]. Being a simple technology, production of RSS is mostly done at cottage level or in small scale. Factories/plants are required for manufacturing of both CL and crepe whilst most rubber plantations in Sri Lanka own crepe rubber processing factories.

Production of raw rubber is a labor-, energy-, and material-intensive process, where a significant amount of electricity and thermal energy, fresh water, firewood, and chemicals are used at different stages of the manufacturing process [5]. Electricity is mainly used in heavy-duty machinery, pumping water, wastewater treatment, and factory lighting. Meanwhile, thermal energy is used for rubber drying and is generated by firewood burning. Fresh water is an important material consumption factor. Water is essential for washing, factory cleaning, dilution of chemicals and field latex, and even for cooling machinery. Furthermore, various chemicals including sodium bisulfite, acids, bleaching agents, diammonium hydrogen phosphate, tetramethylthiuram disulfide and zinc oxide, and ammonia are used in manufacturing different raw rubber types [7][8][9].

Raw rubber processing in natural rubber industry is challenged by low level of material and energy efficiencies, higher degree of wastes and losses, and rising cost of raw materials hence production costs [10][11]. Furthermore, natural rubber processing contributes to numerous environmental problems such as acidic wastewater discharge, malodor caused by rubber particles and chemicals, and greenhouse gas (GHG) emissions [7][12][13]. In meeting the global demand and making the industry competitive, adopting sustainable production strategies in natural rubber production has become indispensable.

Several initiatives have been taken to develop and apply some suitable strategies to address the issues concerned. In view of providing an economical solution for wastewater treatment, Kudaligama et al. [14] proposed and tested a cost-effective wastewater treatment plant. Deploying a water reuse facility at a Thai rubber factory, Leong et al. [15] studied on the reduction in water and treatment costs. Meanwhile, with the aim of resolving high firewood consumption in crepe rubber processing, Siriwardena et al. [16] tested four solar powered drying tower systems and a roof integrated solar air heater-storage system had been the most effective. Also, Rathnayake et al. [17] proposed a single day smoke dryer for RSS production and tested it applying to a factory in Sri Lanka. New system succeeded in drying RSS within a single day without compromising the standard quality of dried RSS. In addition, shortening of drying period had reduced cost of production as it saved firewood and the labor for handling. Tillekeratne [18] also investigated how to reduce the cost of production in a crepe rubber processing factory and found that processing unfractionated and unbleached crepe rubber had been the most effective in this regard, as it avoided the cost for the bleaching agent and saved extra labor cost associated with the removal of yellow fraction. Quantifying the material and monetary losses incurred in concentrated latex and block rubber production in Thailand, Department of Industrial Works [19] provided cleaner technology options that could be effective in reducing the observed losses.

In view of reducing the pollution associated with natural rubber processing, in-plant pollution control guidelines and wastewater discharge standards have already been established by central environmental authority of Sri Lanka [20][21]. Also, several studies have used life cycle assessment (LCA) based approaches to quantify and mitigate the environmental impacts (i.e., emissions) associated with overall natural rubber production process. For instance, Jawjit et al. [7] quantified the GHG emissions associated with the production of RSS, block rubber, and CL in Thailand. This study highlighted that fertilizer and energy use were the leading sources of GHG emissions in Thai natural rubber industry and such emissions could be reduced switching from synthetic fertilizer to animal manure, shifting from fossil fuels to renewable energy, and by energy and fertilizer efficiency improvement. Meanwhile, Jawjit et al [8], investigated the environmental performance of CL production in Thailand with use of LCA and proposed technically and practically viable cleaner technology options for improving the efficiency in consuming energy (i.e., electricity and fossil fuel), ammonia, and diammonium phosphate. GHG emissions in crepe rubber processing have also been appraised stressing the importance of using renewable energy [22]. Taking a different approach, Musikavong et al. [23] quantified the consumptive water use and water scarcity footprint of RSS production in different provinces of Thailand with an ultimate goal of preserving water resources. No records were found on process analyses of crepe rubber manufacture.

All previous studies have taken only a partial approach by investigating either the economic or the environmental aspect of the natural rubber manufacturing process. There have been no studies on the efficiency of the entire manufacturing process. Therefore, this study aims to develop a sustainable manufacturing process in natural rubber processing industry using a novel methodical hierarchy that could be adopted by any other industry. This methodology was based on the process analysis tools of material flow analysis (MFA), material flow cost accounting (MFCA), and life cycle assessment (LCA). Unlike previous studies (i.e., Ulhasanah et. al [24], Nakano et al. [25], and Schaltegger et al. [26]) that combined MFA, MFCA, and LCA, the present study took another step further by integrating Pareto, What-if, and cost benefit analyses into the methodology. Further, it proposes a concrete framework for conducting and continuing an improvement process at a facility for efficient management (please refer to Materials and Methods for more details).

With no any previous studies, processing of one of the principal raw rubber type, crepe rubber, was considered in the present study by investigating a Sri Lankan crepe rubber factory. Crepe rubber manufacturing is severely threatened by various economic and environmental issues and any improvements made in the process could be directly applied in medium/large scale RSS manufacturing. Crepe rubber is considered to be the purest form of natural raw rubber available in the market and Sri Lanka is known as the world’s leading producer of crepe rubber [5]. Due to the high degree of purity, crepe rubber is used to produce pharmaceutical and surgical items that are in contact with human body. However, in our previous research [27], we analyzed the average material flow of the overall crepe rubber manufacturing process. To us, focusing on one factory would give a more specific idea toward developing a financially viable and eco-friendly manufacturing process in any natural rubber factory and an opportunity to test the preceding methodical hierarchy on a more practical level.

4.2. Crepe Rubber Manufacture

Fig. 3.1 illustrates the crepe rubber manufacturing process and the activities that we consider in this study. First, fresh rubber latex (field latex) collected from rubber fields is transported to the factory and unloaded into bulking tanks for the standardization process. Initially in this process, percentage dry rubber content of the field latex (i.e., 30 - 40% by weight of latex [5]) is measured using Metrolac instrument (i.e., a type of hydrometer). Thereafter, proportional to the dry rubber content, sodium bisulfite and water are added into the tanks as a dilutant and a preservative, respectively. After these additions, fractionation tends to occur. Fractionation is a partial coagulation where the yellow fraction is coagulated right after the addition of both the preservative and water. This yellow fraction is usually 10% of the dry rubber mass [3]. After the extraction of the yellow portion, the fractioned latex (white fraction) is passed into coagulation tanks. In the coagulation process, formic acid (coagulant) and bleaching agent are added into the system. Water is also added to dilute the chemicals and make them consistently dispersed across the white fraction. After the coagulation process, coagulum is removed as cubical pieces and sent through a series of roller mills (macerator, diamond roller, smooth roller) to get thin laces of rubber. For the whole milling process, a large amount of fresh water is used for cleaning the laces and bulks, and for machinery cooling. After the milling process, laces are sent to the drying tower for the drying process. The laces are left for three to four days for drying and then sent to the folding section. In this section, crepe laces are placed in a stack form to make 25-kg bulks, and the dirt is removed. Then, the folded mats are passed through two horizontal grooved macerator rollers to make a blanket form. This process is called dry blanket milling. The blankets are trimmed into a broker-specified standard size after removing the dirt on the white crepe bulks. Finally, the packaging process includes visual grading, bundling, and wrapping steps. For wrapping, low density poly ethylene (LDPE) films are used.

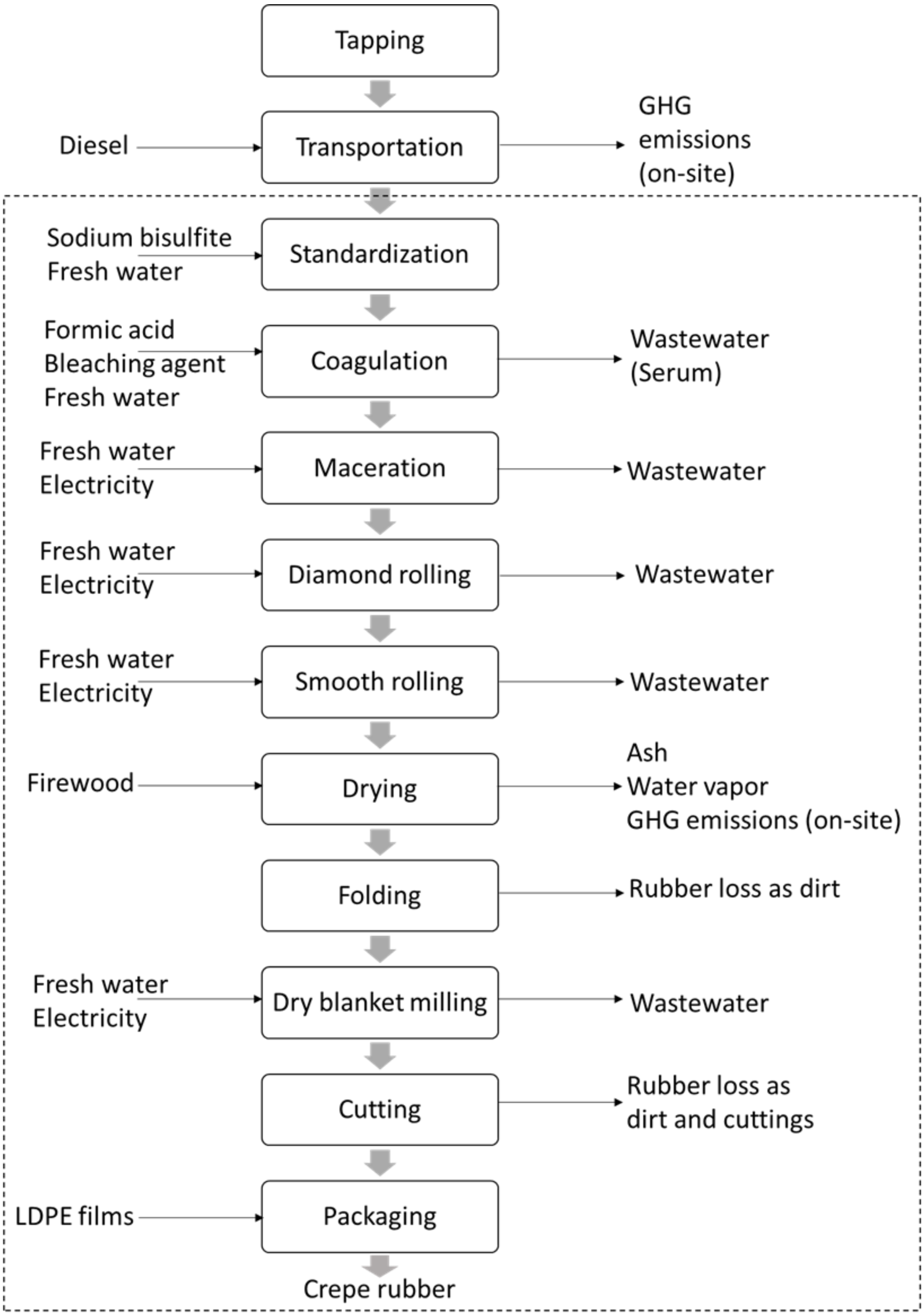

Fig. 4.1. Crepe rubber manufacturing process (Activities considered in this study are demarcated by a perforated line; Code GHG and LDPE refer to greenhouse gas and low density polyethylene, respectively).

4.3. Materials and Methods

4.3.1. Goal and Scope Definition

In view of conducting an in-plant assessment, all activities carried out in a crepe rubber factory were considered in this study. The perforated line in Fig. 4.1 demarcates such activities. Meanwhile, Fig. 4.2 illustrates the entire methodical hierarchy overviewing the techniques and tools integrated. In Fig. 4.2, the perforated line demarcates the scope of the method considered for this study. Further, the raw data inputs, techniques and tools, and their outputs are represented by ovals, rectangles and rounded rectangles, respectively. If briefly explained, the study entailed three steps. In step 1, we employed MFA, MFCA and LCA quantifying the resources used, wastes, mass throughputs, monetary losses, and GHG emissions in the current manufacturing process. In step 2, such information was used to identify key drivers of the system with use of Pareto and What-if analysis. Here, we got the help of factory officials to distinguish easily workable key drivers from less-workable ones. Then, viable improvement strategies for easily workable key drivers were decided interviewing factory officials and other experts who had knowledge of such drivers, and referring to literature. In step 3, the potential benefits of such options and a scenario where all options are in place (combined scenario) were estimated by running MFA, MFCA, and LCA separately. Then, we used simple cost benefit analyses to determine the financial feasibility of each option and the combined scenario. Since the combined scenario was found to be financially feasible, the same was proposed to improve the factory. Further details on the methodology, techniques, and tools are given in the upcoming sections.

4.3.2. Functional Unit

Existing practice and standards for water and chemical inputs in crepe rubber manufacturing are based on the total dry rubber content in latex. Hence, for the sake of simplicity in calculations, all parameters in this study were based on the functional unit of 1 MT of dry rubber input instead of 1 MT of product, i.e., crepe rubber.

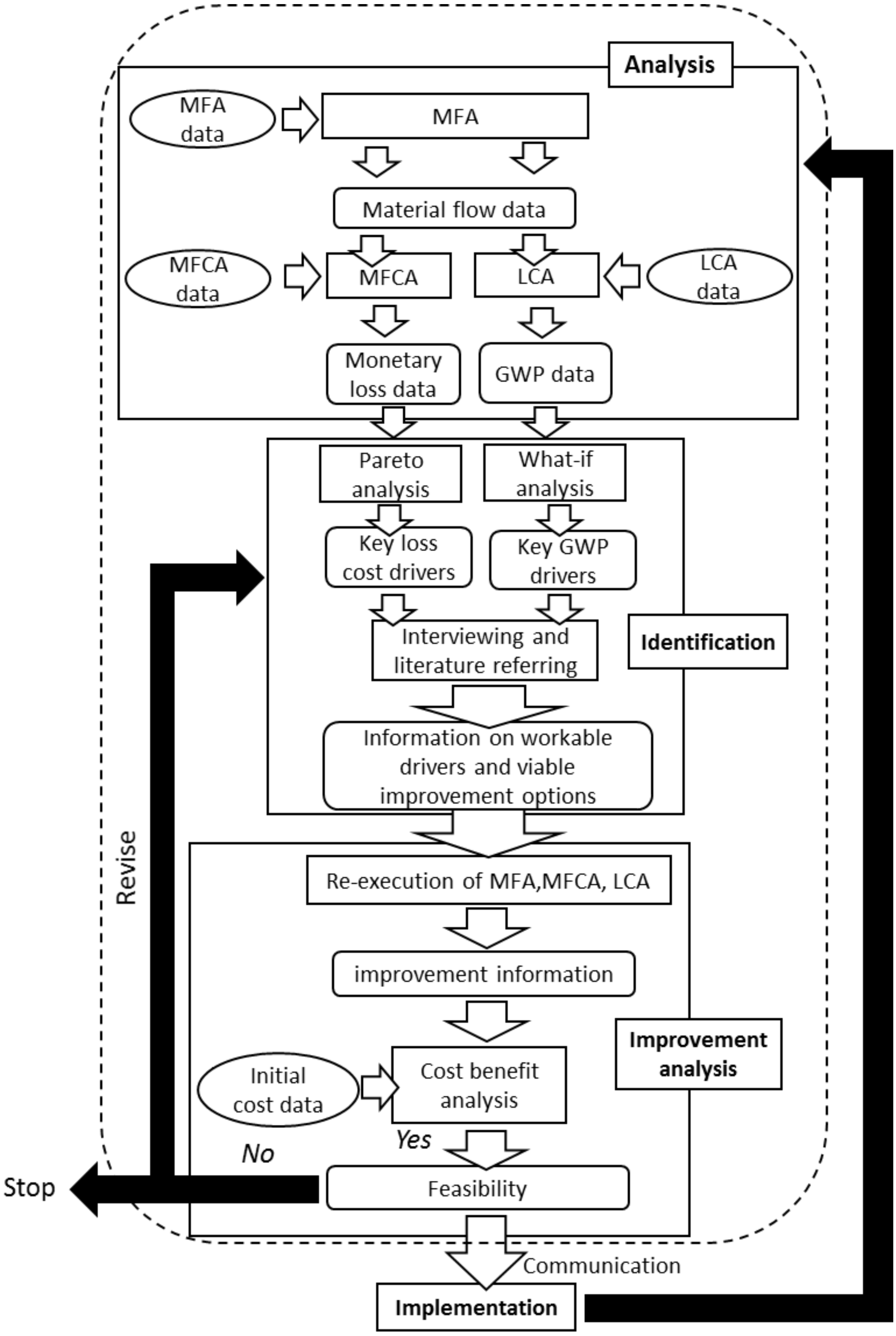

Fig. 4.2. The entire methodical hierarchy overviewing the techniques and tools integrated in the study (Phases considered in this study are demarcated by a perforated line, Reference to the codes are, MFA: material flow analysis, MFCA: material flow cost accounting, LCA: life cycle assessment, GWP: global warming potential).

4.3.3. Data Collection

Data were collected from one of the oldest crepe rubber factories in Sri Lanka during the period of August 2015 to March 2016. The factory had a production capacity of 500 kg rubber/day and employed 50 workers for its operations. Data on water, electricity, packaging materials, and rubber throughputs were collected by on-site measurements. A laboratory assessment was conducted to determine the ash content of rubber wood. Furthermore, factory logbooks and field interviews were used to gather the information on dry rubber content, chemical use, work hours, and rubber losses. Information on the cost of field latex, chemicals, and labor was gathered by accessing factory accounts. Electricity unit prices were collected from the Ceylon Electricity Board home page [28]. Additional data such as machinery depreciation and maintenance costs were collected through field interviews. The emission factors required for LCA were extracted from the literature (Table 4.1). Since the emission factor data on bleaching agent and wastewater treatment were not available, their emissions had to be excluded from LCA.

Table 4.1 Emission factors used for life cycle assessment (LCA). Code LDPE refers to low density polyethylene.

Activity	Gas	Emission factor	Unit	Reference
Production of sodium bisulfite		0.44	kg CO2e/kg	[29]
Production of formic acid		2.51	kg CO2e/kg	[29]
Production of LDPE films		2.00	kg CO2e/kg	[30]
Wood use	CO_2 CH_4 N_2O	110 30 4	kg CO_2/TJ kg CH_4/TJ kg N_2O/TJ	[7]
Generation of electricity (Sri Lanka)	CO_2 CH_4 N_2O	0.417247633 1.64405E-05 3.28811E-06	kg CO_2/kWh kg CH_4/kWh kg N_2O/kWh	[31]
Generation of solar electricity		0.05	kg CO2e/kWh	[32]

4.3.4. Analysis Phase

For the analysis of the current manufacturing process, we deployed the methods of MFA, MFCA, and LCA by considering a functional unit of 1 MT of dry rubber input.

4.3.4.1. Theory of Material Flow Analysis (MFA)

MFA is a systematic assessment of the flows and stocks of material within a system, defined in a space and time [33]. MFA was used to visualize all the material inflows and outflows within the manufacturing system and gain an input-output balance. STAN 2.5 software was used for MFA calculations [34]. STAN 2.5 is a software which delivers a user-friendly graphic-based interface to conduct many MFA calculations including constructing an MFA model and maintaining the input-output balance. Nevertheless, in achieving more illustrative MFA Sankey diagrams, e!Sankey software was used in this study [35].

4.3.4.2. Theory of Material Flow Cost Accounting (MFCA)

MFCA is a tool designed to uplift the eco-efficiency in organizations by focusing on reducing material use, and improving economic and environmental performances [36]. According to ISO 14051: 2011 [37], MFCA considers four categories of cost information as the input data at each quantity center (QC; i.e., unit process): 1. Material cost, 2. System cost, 3. Energy cost; and 4. Waste management cost. Further, it classifies output-cost information bound with material, system and energy costs into two segments (i.e., positive and negative product costs) by multiplying them by the percent of raw material loss by weight at each QC. However, waste management cost is solely allocated to the negative product cost as it is associated with waste. Apart from raw materials, MFCA entails other two types of materials: axillary and operating materials [38]. Auxiliary materials are the materials that are required to produce final product and always end up in final product itself. Operating materials are the materials that are essential to produce final product but always end up as non-product outputs (NPOs), i.e., wastewater and/or emissions.

In view of simplifying MFCA calculations, we integrated the standardization, coagulation, maceration, diamond rolling, and smooth rolling into one quantity center called wet processing. However, the rest of the QCs were allocated to respective sub-processes as usual. List of QCs were as follows: (QC1) wet processing, (QC2) drying, (QC3) folding, (QC4) dry blanket milling, (QC5) cutting; and (QC6) packaging. Herein, general MFCA allocation method was followed at QC3 and QC5 where raw material losses were observable. Meanwhile, input material costs associated with the NPOs (I.e., wastewater containing used chemicals and fresh water) at QC1 and QC4 were solely allocated to the negative material product segment of material cost (i.e., negative material cost) [38]. Furthermore, cost of firewood was considered as an energy cost at QC2. All MFCA calculations were carried out in Sri Lankan Rupees (LKR) on excel spreadsheets. The conversion rate of LKR to US$ is US$ 1=LKR 157.

4.3.4.3. Theory of Life Cycle Assessment (LCA)

LCA is a tool for assessing the potential impacts of a product or service across the whole life cycle, i.e., from raw material acquisition to waste management via production and use phases [39]. In this study, a partial LCA was conducted with an intention of assessing the environmental impacts associated with the production of crepe rubber and was based on ISO 14040: 2006 [39]. Due to insufficient data on emission factors, our LCA was restricted only to assessing the global warming potential (GWP) of GHG emissions. Here, the GWP impact was calculated following an equation used in Jawjit et al. [7] or simply multiplying the conversion factor in “kg CO2e per unit” by the level of activity. The required emission factors (conversion factors) were extracted from literature and are summarized in Table 4.1. However, emissions associated with the manufacturing of bleaching agent and wastewater treatment had to be excluded from LCA due to the unavailability of emission factors. LCA data compiling and calculations were carried out on Microsoft excel spreadsheets.

4.3.5. Identification Phase

We identified the most influential factors that affect the economic losses and GWP using Pareto and what-if analyses, respectively. Pareto analysis is a statistical technique used for distinguishing limited number of factors or tasks that account for overall effect. This technique is rooted in Pareto principle which also known as 80/20 rule. This rule implies that 80% of the effects come from 20 % of causes (factors) [40]. Therefore, with use of a Pareto chart, we identified 20% of loss cost factors that account for 80% of factory`s economic loss. In this chart, the loss cost factors were lined up in a descending order with calculation of cumulative percentage. Any factor that falls completely within 80% of cumulative percentage was regarded as most influential.

What-if/sensitivity analysis is a decision-making tool that can be used to determine how changes in one variable affects the outcome of a model [33]. It is always regarded that the higher the change the greater the sensitivity of the variable. Here, the output of the model was assessed by changing the relevant parameter of GWP model by 5% at a time. Then changes were plotted to form a spider chart as in Fig. 4.5. The most sensitive factor was determined checking the slope of each line. The higher the slope the greater the sensitivity.

Subsequent to the identification of key factors, the discussions with factory officials were held to determine easily workable key drivers from less workable ones. Thereafter, viable improvement measures were suggested based on the discussions held with factory officials, electrical superintendent and engineer, and literature.

4.3.6. Improvement Analysis Phase

The improvement potentials of each option and the combined scenario (which represents the situation when all the options are applied) were evaluated by re-executing MFA, MFCA, and LCA. Furthermore, we conducted cost-benefit analyses for each option and the combined scenario to gain a clear insight into the payback period since it gives an idea of economic feasibility [41].

4.4. Results and Discussion

4.4.1. Results of Analysis Phase

Fig. 4.3 illustrates the descriptive statistics and material flow diagram related to processing 1 MT dry rubber into crepe rubber. Being a Sankey diagram, the width of each flow is proportional to an absolute quantity of mass. However, all the inputs to this production line can be categorized into groups of materials and energy. The only raw material in this production line was the field latex which contains dry rubber. In this case, 1 MT dry rubber included in a 2,755 kg of field latex (i.e., about 36% by weight of latex). As an auxiliary material, LDPE films were used for wrapping the bundles of crepe rubber; 1.67 kg LDPE was required for 1 MT rubber input. There are two types of operating materials; chemicals and fresh water. As mentioned in section 4.4.2, operating materials are the materials that do not end up in the final product, but extremely necessary to manufacture the finished product. Typically, they end up as NPOs, in other words, wastewater. In this manufacturing line, a total of 9.17 kg of chemicals and 76.59 MT of water were used. With the high level of water consumption, a significant amount of wastewater, 77.89 MT, was generated. The amount of wastewater was greater than fresh water input as it contained a portion of water from fresh latex that had been taken out during milling. In addition to the materials, 542.8 kWh of electricity and 394 kg of firewood were used as the energy-related inputs.

Table 4.2 Demonstration of material flow cost accounting (MFCA) cost matrix. Cost values are given in Sri Lankan Rupees (LKR) per 1 MT rubber inputs with the fraction (%) from total manufacturing cost in parenthesis (Reference to the codes are, MC: Material cost, SC: System cost, EC: Energy cost, WMC: Waste management cost).

	MC	**SC**	**EC**	**WMC**	**Total**
Positive product cost	170,138 (80.3%)	19,762 (9.3%)	3,703 (1.7%)	0 (0.0%)	193,602 (91.3%)
Negative product cost	12,015 (5.7%)	729 (0.3%)	167 (0.1%)	5,240 (2.5%)	18,151 (8.7%)
Sub-total	182,153 (86.0%)	20,491 (9.6%)	3,869 (1.8%)	5,240 (2.5%)	211,753 (100%)

As shown in Table 4.2, the highest negative product cost comes from the negative material cost segment with a value of about 5.7% of total input cost. Waste management cost was about 2.5% of total input cost, whilst the contributions from negative energy and system cost segments to total negative product cost remained negligible. The total negative product cost was LKR 18,151 and accounted for 8.7% of total input cost.

Fig. 4.4 illustrates the MFCA of crepe rubber manufacturing process. It highlights that four out of all six processes (i.e., wet processing, folding, dry blanket milling, and cutting) of that manufacturing process incur negative product costs. The highest negative product cost occurs in wet processing with a value of LKR 9,303 contributing to about 4.4% of the overall manufacturing cost. This negative product cost comprised waste management and negative material costs, which derive from the costs that put into wastewater treatment and the costs that wasted with NPO. The second and third largest negative product costs occurred at QC3 and QC5, respectively, and are mainly affected by negative material costs. However, the rest of the QCs had either negligible or no contribution to negative material costs.

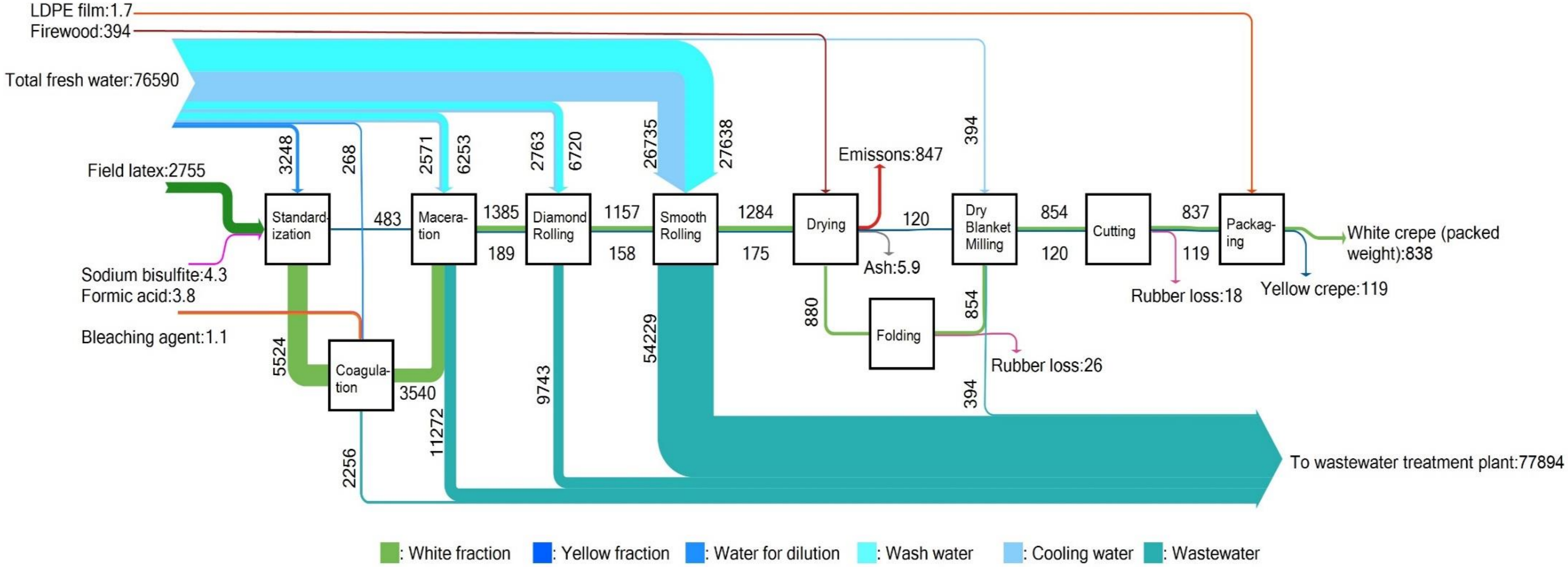

Fig. 4.3. Material flow in the crepe rubber manufacturing process [kg/MT of rubber input]. Thickness of the lines is proportional to the quantity of flow. Code LDPE refers to low density polyethylene.

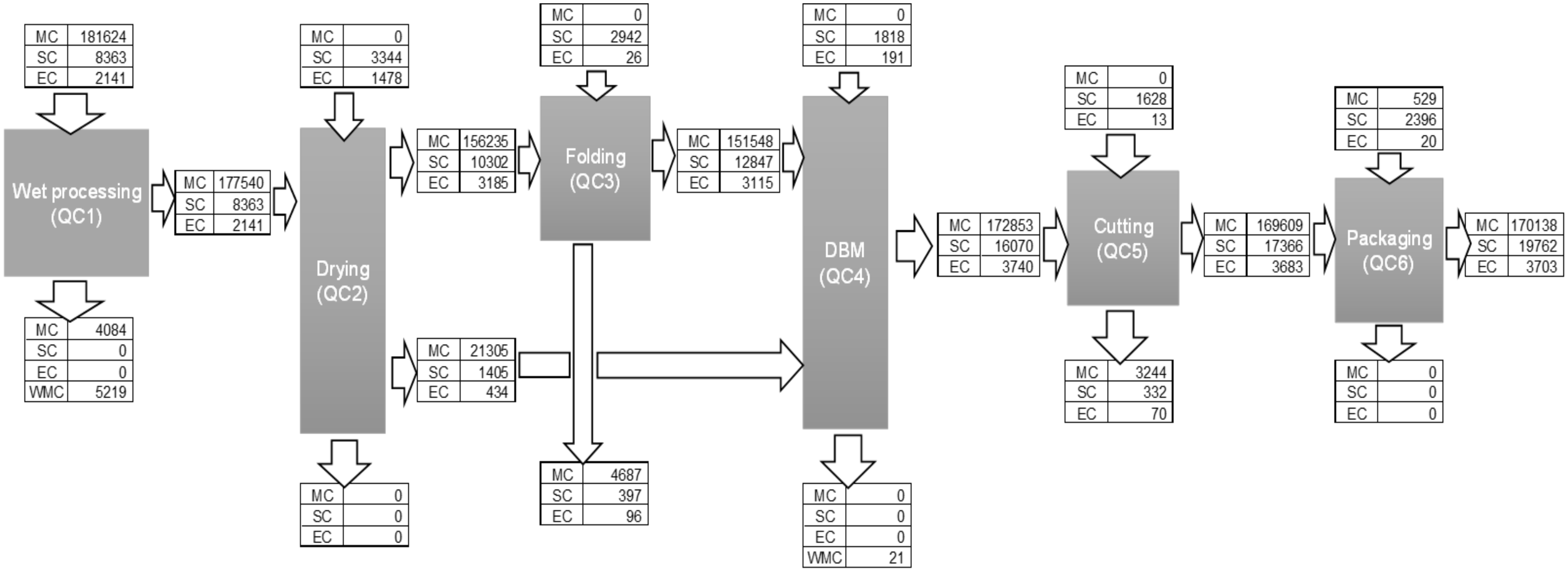

Fig. 4.4. Summary of Material Flow Cost Accounting (MFCA) of crepe rubber manufacturing process [Sri Lankan Rupees (LKR)/MT of rubber input] (Reference to the codes are, QC: quantity center, MC: material cost, SC: system cost, EC: electricity cost, WMC: waste management cost).

Table 4.3 illustrates the results of LCA and break down of GWP according to the activities involved. The total GWP impact associated with processing 1 MT of dry rubber was 254.2 kg CO_2e which was less than the average GWP, 279.3 kg CO2e, recorded in our previous study [27]. Use of gravity for pumping water to the factory was the reason for such deviation. The largest contributor to GWP was found to be the electricity consumption. Whilst the manufacturing of chemicals and firewood combustion contributed moderately to GWP, the manufacturing of LDPE films had contributed negligibly to GWP.

Table 4.3 Global warming potential (GWP) breakdown of crepe rubber processing system (per 1 MT of rubber input). Code LDPE refers to low density polyethylene.

Activities	GWP impact [kg CO_2e]	% of total
Generation of electricity	227.2	89.3
Manufacturing of chemicals	11.4	4.8
Firewood combustion	12.3	4.8
Manufacturing of LDPE film	3.3	1.1
Total	254.2	100.0

4.4.2. Results of Identification Phase

Table 4.4 summarizes the results of the Pareto analysis on economic losses. Key factors that fall within the 80% economic loss could be identified as waste management cost at wet processing (QC1), negative material cost incurred by rubber dirt (rubber loss) at folding (QC3) and negative material cost associated with NPOs at wet processing (QC1). According to the discussions held with factory officers and managers, we identified waste management and negative material costs associated with NPOs at wet processing as the easily workable drivers in the system. However, reducing rubber dirt at folding was not straight forward due to the influences of some other sub-determinants (e.g., handling errors, milling errors, dirty rollers, improper chemical addition, etc.). For reducing waste management cost at QC1, the amount of wastewater per 1 MT of rubber input is to be reduced decreasing fresh water requirement. Meanwhile, reduction in NPOs could be achieved through reducing chemicals. As per discussions and practicability in adoption, the following approaches are proposed.

Table 4.4 Summary of the Pareto analysis for negative costs per 1 MT rubber input (Reference to the codes are, LKR: Sri Lankan Rupees, NMC: Negative material cost, NSC: Negative system cost, NEC: Negative energy cost, WMC: Waste management cost, WW: wastewater, NPO: non-product output, NPC: negative product cost, QC: quantity center).

Category	NPC [LKR]	% of total	Cumulative percentage [%]
WMC (WW) at QC1	5,219	29	29
NMC (Dirt) at QC3	4,687	26	55
NMC (NPO) at QC1	4,084	22	77
NMC (Edges) at QC5	1,729	10	87
NMC (Dirt) at QC5	1,515	8	95
Others	917	5	100
Total	18,151	100	100

Option 1: Reduction in water use

To reduce water consumption, we suggested the factory to replace leaky pipes, joints, and valves with new fittings and to fix a digital water meter to the water supply of each machine at wet processing. We further proposed them to assign a fixed water flow rate to each machine at wet processing. By using the aforementioned digital water meters, the assigned flow rates can accurately be ascertained. In this factory, water discharged due to machinery cooling was in a pure state that could easily be reused. Therefore, we recommended factory to install an industrial water recirculation cooling system (IWRCS) that can chill and recirculate the cooling water at a constant flow rate. Information on the most suitable IWRCS for the factory was obtained contacting a company specialized in such systems.

Option 2: Reduction in chemical use

In reducing chemical use, we suggested factory to measure the dry rubber content for the second time during the coagulation stage to confirm the amount of dry rubber that has streamed into the settling tanks as a result of fractionation at standardization process. Here, the dry rubber content can easily be measured by taking Metrolac readings of the latex samples taken from settling tanks. The Metrolac instrument (i.e., a type of hydrometer) already in use at the factory can be used to take those readings.

Fig. 4.5 illustrates the outcome of the what-if analysis on factors influencing GWP. Being the steepest, the yellow trend line representing electricity showed the highest sensitivity to GWP. Therefore, even a slight reduction in electricity would result in a considerable reduction in GWP. Effects of other factors were found to be negligible in global warming.

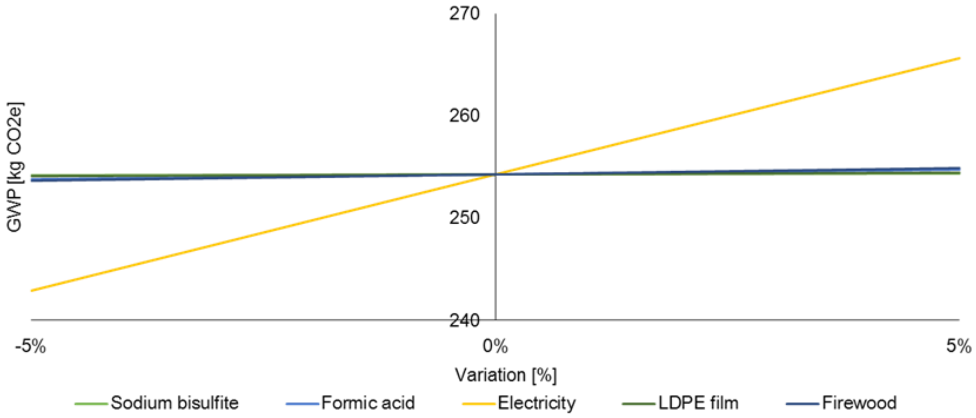

Fig. 4.5. Illustration of what-if analysis for factors affecting the global warming potential (GWP). Code LDPE refers to low density polyethylene.

Option 3: Reduction in electricity

Although the electricity consumption for machinery was the highest component in overall electricity use, its reduction options such as replacing old motors and machinery seem impractical due to the extremely high capital costs involved. For such a reason, as a low cost option, we proposed replacing old compact fluorescent lamps and tube lights with new LED lamps delivering the same brightness. As the factory situated in the tropical climate where plenty of sunlight being shed, we advise factory to install solar panels after referring to the officials` opinion. They highlighted that such an option remained practically possible because it does not take as high investment as replacing old machinery. Based on the present study, the management of the factory is preparing to get solar panel fixed for obtaining cleaner energy for factory running. By contacting a company specialized in solar panels, the appropriate capacity for solar panels was determined. Other information such as cost per kW, area covered, tariff schemes, and total project cost was also obtained.

4.4.3. Results of Improvement Analysis Phase

Option 1: Reduction in water use

This option could reduce the production system`s water consumption by 45.59 MT (per 1 MT rubber input) resulting in the reduction of waste management costs of wet processing from LKR 5,219 to LKR 4,191. The overall total negative product and overall manufacturing costs could be reduced from LKR 18,151 to LKR 17,123 and from LKR 211,753 to LKR 210,725, respectively. This option could lessen the GWP impact per 1 MT rubber input from 254.2 kg CO_2e to 252.6 kg CO_2e due to the reduction in the electricity consumed for wastewater treatment. However, the extra electricity required for water recirculating system restricts gaining a notable drop in GWP. As per the simple undiscounted cash flow analysis, payback period for this option was found to be approximately 4 years.

Option 2: Reduction in chemical use

Although the chemical reduction measures could not significantly reduce the amount of formic acid (coagulant) and the bleaching agent, they could decrease the material loss costs from LKR 12,015 to LKR 11,943 (per 1 MT rubber input). However, its effects on GWP was negligible. This option does not take any extra cost, and therefore, will be beneficial from the very moment it is applied.

Option 3: Reduction in electricity

Energy calculations showed that LED installations have reduced total electricity consumption by 7.1 kWh from the original value of 542.8 kWh (per 1 MT rubber input) and the remaining 535.7 kWh was generated on-site by solar panels. Therefore, GWP reduction had been remarkable as it came down to 53.8 kg CO2e from 254.2 kg CO2e per 1 MT rubber input. Meanwhile, negative product and total manufacturing costs reduced by LKR 3,708 and LKR 4,131 (per 1 MT rubber input), respectively. Simple payback period for this option was recorded as 13 years.

Combined scenario: Application of options 1, 2, and 3

Fig.4.6 and Fig. 4.7 illustrate the improved material and cost flows under the combined scenario, respectively. The most noticeable aspect in Fig. 4.6 is the water loop belongs to option 1. It circulates about 16,701 kg of water dedicated for machinery cooling in processing 1 MT rubber input. Reduction of waste management cost is influenced by both options 1 and 3. Therefore as shown in Fig. 4.7, waste management cost at wet processing have notably reduced from LKR 5,219 to LKR 640 (per 1 MT rubber input). Here, option 1 reduces waste management cost by reducing the wastewater amount; thereby energy and other costs bound with waste management cost itself will decline. Meanwhile, option 3 does the same task by replacing costly electricity required for waste management with self-generated solar electricity. In addition, input material and negative material costs of wet processing have dropped down to LKR 181,552 from LKR 181,624 and to LKR 4,012 from LKR 4,084, respectively. Such reductions depict the efficacy of option 2. Also, input electricity costs at all QCs have either been reduced or reached 0, which shows the effectiveness of solar energy introduced in option 3. In view of summarizing all cost reductions, we provide Table 4.5. Accordingly, all options reduce total negative product cost by LKR 4,695 per (1 MT rubber input), which corresponds to a 26% drop. Total input cost per 1MT of dry rubber has also gone down to LKR 206,622 from LKR 211,753 and is a reduction of 2.5%.

Fig. 4.8 illustrates the potential reduction of GWP from the existing situation (baseline) to the combined scenario. Overall reduction is 79%, mainly due to the installation of solar panels under the option 3 which completely cut off the fossil- based electricity while accounting for a 200.6 kg CO2e reduction in GWP impact.

If extrapolated, overall improvements may reduce the usage of 7,116 MT of water, 17 kg of chemicals, and 84.8 MWh of electricity per year saving about LKR 801,159 of cost and 31.3 MT CO2e of GHG emissions per year in this particular factory. Simple payback period for this scenario was recorded as approximately 11 years.

Table 4.5 Cost distribution comparison between baseline (indicated in black letters) and combined scenario (indicated in black bold letters). Cost values are given in Sri Lankan Rupees (LKR) per 1 MT rubber inputs. (Reference to the codes are, MC: Material cost, SC: System cost, EC: Energy cost, WMC: Waste management cost).

	MC	**SC**	**EC**	**WMC**	**Total**
Positive product cost	170,138	19,762	3,703	0	193,602
	170,138	21,641	1,387	0	193,521
Negative product cost	12,015	729	167	5,240	18,151
	11,943	802	65	646	13,456
Sub-total	182,153	20,491	3,869	5,240	211,753
	182,081	22,443	1,452	646	206,622

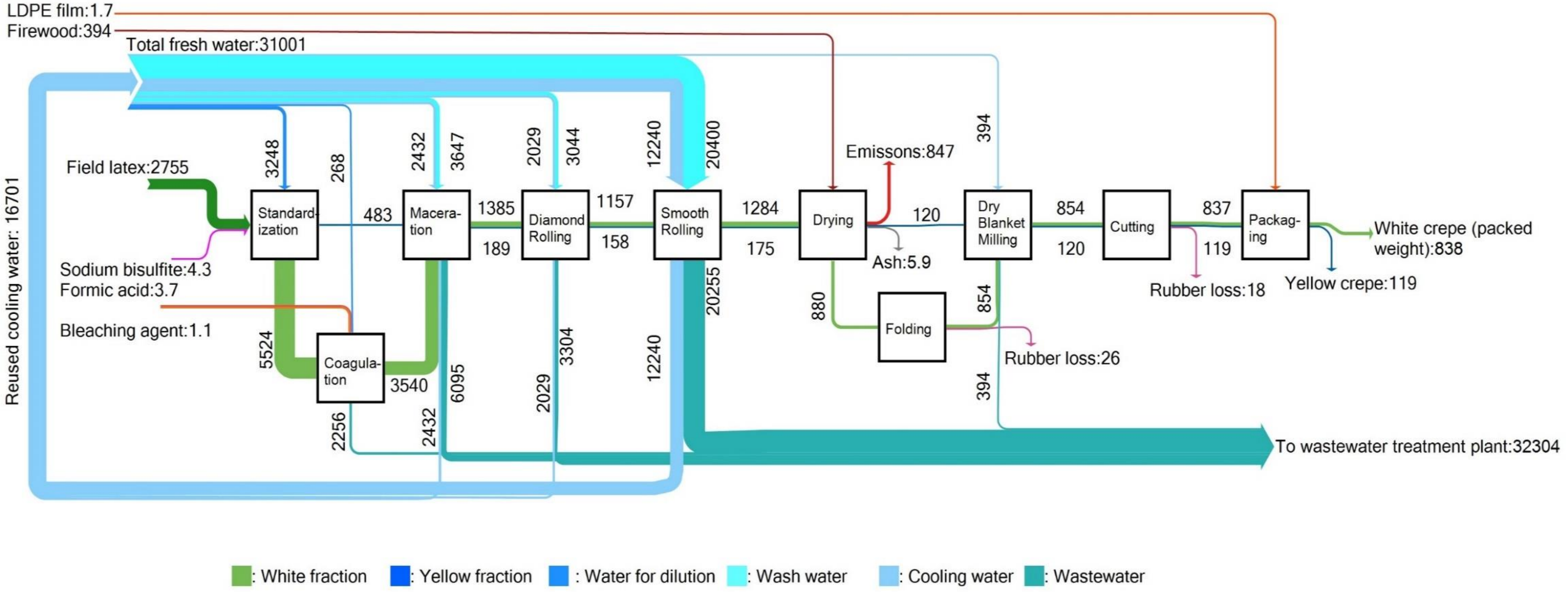

Fig. 4.6. Improved material flow of the crepe rubber manufacturing system due to the combined scenario [kg/MT of rubber input]. Thickness of the lines is proportional to the quantity of flow. Code LDPE refers to low density polyethylene.

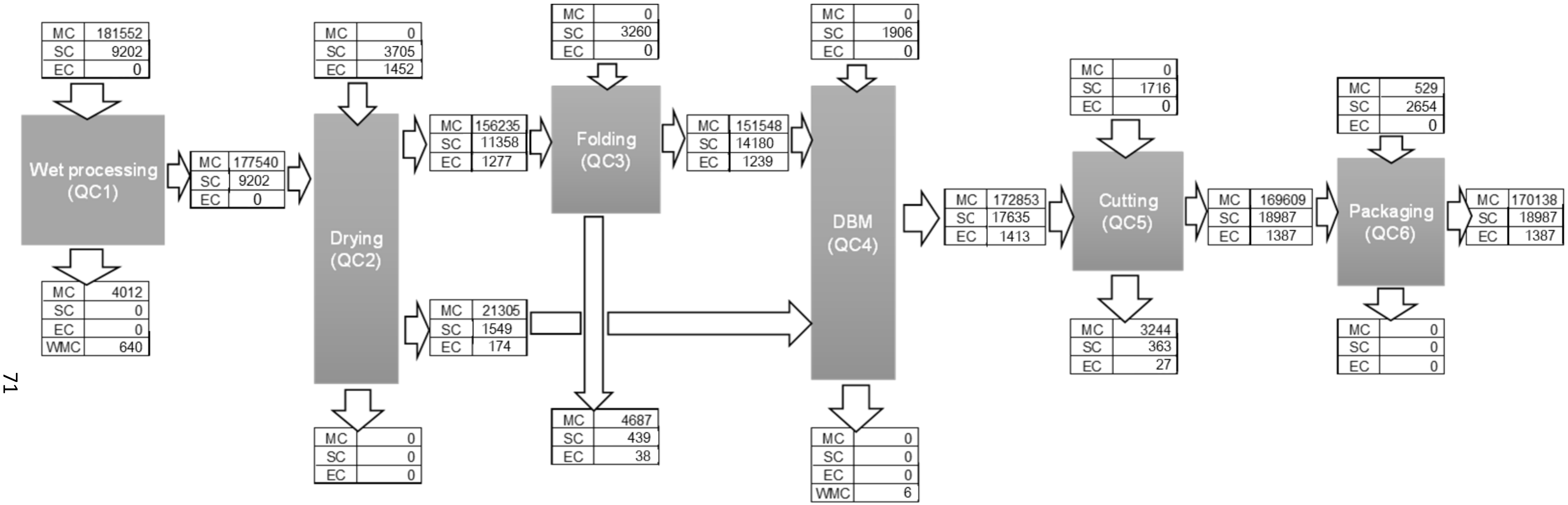

Fig. 4.7. Improvements in material flow cost accounting (MFCA) of crepe rubber manufacturing system due to the combined scenario [Sri Lankan Rupees (LKR)/MT of rubber input] (Reference to the codes are, QC: quantity center, MC: material cost, SC: system cost, EC: electricity cost, WMC: waste management cost).

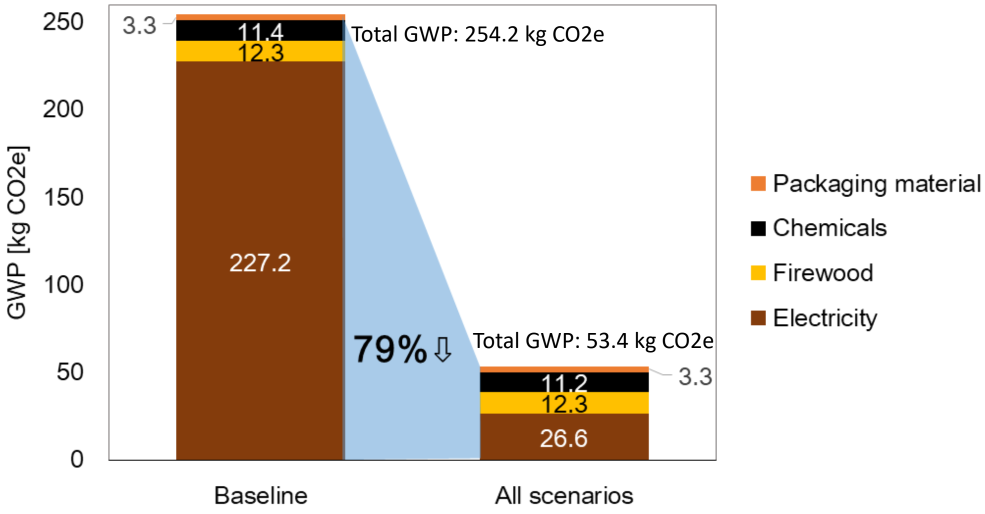

Fig. 4.8. Illustration of potential reduction in global warming potential (GWP) due to the proposed improvements. Values are given per 1 MT rubber inputs. Baseline refers to the existing levels.

4.4.4. Importance of the Findings to Natural Rubber Sector

The overall results showed that the current crepe rubber manufacturing system at the factory level could considerably be improved addressing the issues of high cost of manufacturing and GHG emissions. As shown in the extrapolation to the annual scale, the improvements proposed would result in substantial decline in the usage of water, chemicals and electricity and, reduction in costs and GWP in long-term.

Water savings will preserve adjacent water resources from exploitation and minimize the excess burden exerted by loads of wastewater [42]. According to the factory manager, this factory experienced wastewater overflows at the treatment plant during the high cropping months (i.e., peak yielding season). Such improper wastewater treatment results in environmental problems, sometimes receiving the complaints from nearby residents. He further reported that during the dry season, the factory had to transport water from outside using bowsers because adjacent water sources failed to supply sufficient water for its operations. The use of bowsers adds an extra costs and a burden on the environment because of additional fuel combustion. Therefore, the water reduction measure discussed in this study could provide timely solutions for all these issues.

Chemical savings would not only save costs but also reduce wastewater toxicity [43]. Less toxicity would make the treatment easier and reduce the chemical odor at wastewater treatment plant. Use of solar power provides financial benefits as well as less CO_2 emissions. It may also to contribute to create less demand for primary fuel (e.g., coal, gas, oil, etc.) in the long run whilst curbing risks associated with their extraction processes (e.g., environmental contamination from mining operations, drilling leaks, and explosions, etc.). Amidst the Sri Lankan government's new project (i.e., called Battle for Solar Energy) [44] for promoting solar energy across households, hotels, commercial establishments and industries in the island, we believe that benefits highlighted in this research would give an extra encouragement to opt for solar energy in raw rubber processing factories.

Being cost effective and more ecofriendly, the proposals made will ultimately facilitate the rubber production industry to be competitive in the global market whilst uplifting its corporate image. At local level, such outcomes may result in building healthier relationships with the surrounding community and creating positive public image while upgrading the factory`s reputation. Uplifted factory reputation may further boost workers morale by fostering teamwork and continuous improvement, thereby leading to improvements in working conditions [45].

This study took an initial step towards improving a natural rubber factory by proposing three practicable options. If interested, the reductions achieved herein can be enlarged by some other options. Especially, the electricity can further be reduced by installing new machines, motors, skylights, windmills, and power factor corrections. Even the biogas generated at anaerobic digester of water treatment plant can be utilized directly to furnace used in rubber drying and perhaps to produce electricity [46]. If used for electricity, it can be utilized for in-factory operations and will reduce electricity tariff or in our case spare solar energy units. Since the current net metering and net accounting schemes in Sri Lanka allows trading such units to the electric utility, gaining extra revenues will be possible. On-site use of methane in either way (in place of firewood or electricity) will ultimately result in drop of GWP. In the present study, such options could not be applied due to the financial and geographical background of the audited factory.

If we attend to reducing dry rubber losses, for instance, reducing rubber being removed as dirt at QC 3, negative product cost can further be cut down significantly. Usage of cause-effect diagrams may facilitate this process by unveiling relationships among sub factors affecting dirt. However, these initiatives are yet to be tested and their practicability must carefully be reviewed in future research.

Although natural rubber sector shows a tendency to attend sustainable management practices, some barriers still exist. For instance, lack of expertise in process analysis tools and techniques, in-plant operations, prioritizing profits and market share, and managing high initial costs are evident. Further, it was evident that factories refrain from sharing successful practices in order to be more competitive over fellow factories.

4.4.5. Pros and Cons of Methodical Hierarchy

Findings clearly indicate that the methodical hierarchy introduced in this study had been effective in terms of pinpointing inefficiencies and improving economic and environmental performances of a natural rubber factory. On the other hand, this method can become costly and time-consuming, as it requires lot of expertise and data. Until the factory becomes familiar with the techniques and tools used in this study, we recommend them to hire an expert in the relevant field. Once they get familiar, factory itself may handle the improvement process at ease with no extra cost on experts.

Not evaluating social impacts is another limitation of this method. Social life cycle assessment (SLCA) can be added to the analysis phase in order to evaluate direct social impacts of a factory or production system [47]. Adding other impact categories (e.g., ozone layer depletion, eco-toxicity, eutrophication, etc.) to LCA would unveil a new set of environmental hotspots that went unnoticed in the present study. In addition, a company which is more eco-conscious may use an index such as "GWP payback period" during the improvement analysis phase. It may give an idea about the period after which the GWP caused by an option can be recovered. For example, in our case, GWP associated with solar panels and LED lamps can be divided by their GWP savings per year, in order to get GWP payback period of option 3. Data on manufacturing solar panels and LED lamps can either be obtained through literature or performing a simple LCA.

Implementation phase of the methodology will have to be carried out after communicating the outcomes to the staff. In such a case, a workshop can be arranged not only to transfer the outcomes to the staff effectively but also to broaden their knowledge in sustainable manufacturing.

4.5. Conclusions

The main objective of this study is to develop an economically viable and environmental friendly natural rubber production process using a novel method. A case study was performed in a crepe rubber manufacturing factory in Sri Lanka. The study revealed that factory currently generates 77.89 MT of wastewater, 44 kg of dry rubber waste, and 5.9 kg of ash per 1 MT of rubber input, showing inefficient use of water, chemicals, and electricity. The improvement options proposed herein have led to reduction in 45.59 MT of fresh water, few grams of chemicals and 542.8 kWh of electricity. These reductions also save 26% of cost and reduce the current GWP by 79%. Being practically feasible, the options recognized in this study are to be adopted by the management of the factory, as the next step. They may also try other options mentioned in this study during the continuous improvement process. To us, these savings and reduction can ultimately result in increase of profits, reduction in toxic gases released in to air, water conservation, and uplifted corporate image.

Despite there are some barriers to sustainable management practices in natural rubber sector, the methodical hierarchy introduced in this study can be very useful in achieving the ultimate target of sustainability not only in natural rubber sector but also in other sectors rooted in developing countries.

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CHAPTER 5 Improving Financial and Environmental Sustainability by Combining Process Analysis Tools with Pareto, What-if, Economic and Environmental Feasibility Analyses: A Study of Concentrated Latex Manufacture

5.1 Introduction

Natural rubber is an indispensable commodity for mankind; having unique qualities, it is the principal raw material for several essential products (e.g., tires, tubes, surgical gloves, condoms, etc.) required by humans [1]. Natural rubber is originated from fresh latex obtained by tapping rubber trees. Tapped latex is collected into containers fixed to the trees and manhandled or transported to a near-by rubber factory for processing into a usable form called raw rubber. This raw rubber is eventually reprocessed into value-added natural rubber products in separate factories. Concentrated latex (CL), crepe rubber, ribbed smoked sheets (RSS), technically specified rubber (TSR) are the main types of raw rubber in the industry [2]. Among them, CL holds a momentous position as it is the based material of dipped rubber products such as gloves, balloons, condoms, rubber thread and infant pacifiers. The share of CL in raw rubber production in the world is ca. 50% and the majority (ca. 85%) comes from Asian tropical region [3]. Being one of the leading dipped rubber product manufacturers in this region, Sri Lanka had produced 20,497 MT of CL in 2016 accounting to ca. 26% of total natural rubber produced in the country [4]. In Sri Lanka, CL has mainly been produced in small- and medium-sized factories having a capacity of less than 1000 kg per day [5].

The production of CL is a labor-, energy-, and material-intensive process; significant amounts of electric and/or thermal energy, diesel fuel, fresh water, and chemicals are used at different stages. Efficiency of this process is to be reviewed due to high level of wastes, rising cost of manufacture [6][7][8]. Also, numerous environmental issues exist with acidic wastewater, malodor caused by rubber particles and chemicals, and the emission of greenhouse gasses [2][9][10].

Several studies have been conducted to address the above-mentioned issues. The Department of Industrial Works (DIW) in Thailand has investigated on the possibility of uplifting the production efficiency of Thai CL processing sector through waste minimization [11]. Therein, DIW tried establishing a set of standards for chemical, water and energy use, and loss in latex content using the median values for random samples of CL factories in Thailand. Meanwhile, Peiris [6] and Yasaratna [12] outlined number of cleaner production measures to uplift the profitability and productivity with lesser environmental load in CL processing by reusing and recycling water, de-ammonization of skim portion, mechanized skimming, planning milling time, good housekeeping practices. Wastewater discharged from CL factories is sulfate-rich and highly acidic due to sulfuric addition demanding a proper treatment of wastewater with a set standard before discharge into the environment [13]. In this regard, several anaerobic wastewater treatment plants and related strategies had been introduced and tested by several studies. For instance, Rubber Research Institute of Sri Lanka [14] introduced a low cost anaerobic wastewater treatment plant to a crepe rubber factory. Being successful during the pilot stage, commercial-scale treatment plants have now been installed in number of crepe rubber and CL factories. However, anaerobic treatment of wastewater with a high sulfate content causes malodor problems generating sulfide. Therefore, sulfate reduction reactors (SRRs) have been introduced in this regard. For example, Chalong Latex Industry Co.,Ltd. [15] combined a SRR with an up-flow anaerobic sludge blanket system (USAB) to generate biogas as thermal energy source for a CL factory. As this biogas minimizes the use of liquid petroleum gas (LPG) bound with in-factory operations, a significant amount of cost could be saved. In view of appraising the environmental impacts associated with CL processing sector in Thailand, Jawjit et al. [16] conducted a partial life cycle assessment involving three Thai CL factories and ascertained that electricity, diesel and chemical use were the prominent factors affecting these environmental impacts. Efficient use of chemicals and electricity, and substituting diesel by LPG had been effective in this context. Similarly, Jawjit et al. [2] and Wijaya et al. [17] quantified the greenhouse gas (GHG) emissions associated with CL manufacture in Thailand and Indonesia, respectively ascertaining that electricity consumption is a major contributor to GHG emissions. Installation of inverters to centrifugal machines has been proposed as an option for minimizing electricity [2][16].

Lacunas exist in previous studies due to partial approaches taken to address an issue or a set of issues that attributed to either economic or environmental aspect in CL manufacture. No studies to date have quantified the material use and waste, monetary losses, and environmental impacts of entire CL manufacturing process together. This has hindered identifying actual economic and environmental hotspots and thereby providing adequate solutions to key drawbacks in the manufacturing process. Therefore, this study aimed at conducting an assessment in view of developing energy efficient, less polluting and financially more viable process for manufacturing of CL after identifying the actual environmental and economic hotspots. This assessment was based on a framework that integrates process analysis tools of material flow analysis (MFA), material flow cost accounting (MFCA), and life cycle assessment (LCA) to appraise material flows, monetary losses, and environmental impacts, respectively in CL manufacture. Surpassing the theoretical boundaries of previous studies (i,e., Ulhasanah et al. [18], Nakano et al. [19] and Schaltegger et al. [20]), this framework deployed Pareto and What-if analysis to pinpoint actual hotspots for facilitating selection of improvement options. The degrees of improvement that can be reached through the nominated options were determined by re-executing MFA, MFCA, and LCA. In view of getting an insight into the economic and environmental returns of the improvements, our framework further integrated discounted cash flow analyses (DCFA; i.e., net present value (NPV), internal rate of return (IRR), discounted payback time (DPBT)) and greenhouse gas payback time (GPBT) indicator. Finally, overall efficiencies of the nominated options were evaluated introducing a novel index called ‘loss reduction efficiency` (LRE) index in terms of both financial loss and environmental impact minimizations, DPBT and GPBT. This approach was somewhat similar to the frameworks in appraising financial and environmental sustainability in crepe rubber manufacture [8][21]; however in addition, it carried a uniqueness in view of conducting a comprehensive assessment in raw rubber manufacture due to the inclusion of DCFA, GPBT and LRE index.

5.2. Concentrated Latex Manufacture

The process of CL manufacture is illustrated in Fig. 5.1. Firstly, fresh field latex collected from rubber plantations after tapping the trees is transported to the factory by bowsers. When field latex arrives at the factory, percentage dry rubber content (%DRC) and ammonia concentration in latex are determined by a lab test. Then, the latex is unloaded through a 60-mesh sieve into bulking tanks, for bulking process. At the bulking tanks, a mixture of tetramethylthiuram disulphide (TMTD) and zinc oxide (ZnO) (commonly called as TZ), diammonium hydrogen phosphate (DAHP), and lauric soap are added. Here, DAHP acts as a remover of magnesium ions while others act as preservatives. Removal of Mg^{2+} is important because the presence of Mg^{2+} enhances the bacterial growth. Here, Mg^{2+} is removed in the form of magnesium ammonium phosphate via decantation. Thereafter, the remaining field latex is sent to centrifuge separators, for centrifuging. At the separators, field latex is broken down into two segments; CL and skim latex where %DRC is about 60% and 3-6%, respectively. Steel tanks are used to preserve CL of which ammonia content is maintained considering the customer need, i.e. either as high ammonia (about 0.7%) or low ammonia (about 0.2%), till dispatch. Skim latex is let into a separate tank (i.e. coagulation tank) where it is coagulated using sulfuric or formic acid for coagulation. Coagulum is then extracted and milled to get sheets of skim rubber. Later, the laces are air-dried and transformed into rubber blankets by mechanical pressing (dry blanket milling). Finally, these blankets are trimmed into tile-shaped segments and packed as skim crepe.

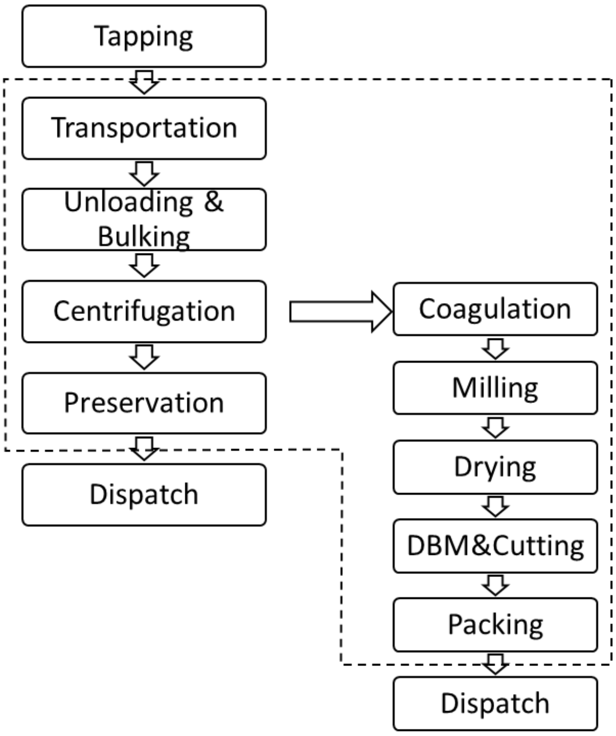

Fig. 5.1. Concentrated latex manufacture. Perforated line demarcates the system boundary considered herein. Code DBM refers to dry blanket milling.

5.3. Methodology

5.3.1. Goal Definition

This study followed three steps to meet the objectives: 1) analyses on the current CL manufacture in order to quantify material use, waste, monetary losses, and greenhouse gas (GHG) emissions, 2) identification of hotspots and proposal of applicable improvement options, and 3) efficiency evaluation of the proposed improvement options.

5.3.2. Step 1: Quantification

In order for quantifying waste, financial losses and GHG emissions of CL manufacture, we used process analysis tools of MFA, MFCA and LCA, respectively.

5.3.2.1. System Definition

Transportation of field latex, and manufacturing process within CL processing factories were the focus of this study (see Fig.5.1). Activities bound with rubber plantations were excluded due to following reasons: 1. high degree of temporal and spatial variability of rubber cultivations (this needs to be addressed by a separate study) [21]; and 2. net CO_2 emissions from rubber plantations have been identified negative even after the inclusion of CO_2 emissions from fertilizer use and vehicular activities [22]. Emissions associated with the production of other inputs (externalities) such as electricity and chemicals (i.e., formic acid, ammonia, zinc oxide, lauric acid and sulfuric acid) were taken into overall emission calculation. Factories undertaken for the study usually produced low ammonia concentrated latex unless any special request for high ammonia concentrated latex from customers. Therefore, the study was based only on the production of low ammonia concentrated latex.

5.3.2.2. Functional Unit

A functional unit of 1 MT of dry rubber input was considered in all calculations. Weight of field latex mentioned on material flow diagrams is reported in wet basis. Typically, field latex is constituted of 30%-40% dry rubber and 60%-70% of non-rubber particles and water [23].

5.3.2.3. Data Collection and Compilation

The study was conducted in three CL factories (factory A, B, and C) scattered over three major rubber producing districts in Sri Lanka, i.e. Kegalle, Kurunegala, and Gampaha. These districts account for over 60% of the rubber land area in the island [4]. Data were gathered by visiting all factories in person. Rubber throughputs, electricity and water consumption were measured on site. Rubber content of field latex being washed out in terms of %DRC, and percentages of other probable rubber losses were ascertained by lab experiments or interviewing factory officers. Information on diesel consumption, values of %DRC in field latex, CL and skim latex outputs, and water quantities for cleaning bowser, bulking tank and centrifuge bowl was collected by referring to factory logbooks and conducting interviews with factory officers, other staff of factories, estate managers and owners.

Costs on field latex, diesel, chemicals, staff, labor and wastewater treatment were extracted from factory accounts while industrial electricity tariffs were taken by referring to the home page of Ceylon Electricity Board [24]. Further, data required to calculate machinery depreciation and maintenance costs were collected interviewing factory officials. All CL factories possessed similar production capacities, manufacturing processes, and wastewater treatment plants. However, differences in chemical addition was observed; factories followed their own standards and practices in adding chemicals. Further, factory A and B used sulfuric acid for coagulating skim rubber whilst factory C used formic acid. Therefore, the term `acid use` is used herein as a common term for both sulfuric and formic acid usage, where necessary.

Emission factors required for LCA were extracted from AIST-LCA ver.4 database [25] and literature. Due to lack of emission factor data on TMTD manufacture, we had to exclude its emissions from LCA (for more details on emission factors please refer Table 5.1).

Table 5.1. Emission factors used in step 1. Code DAHP and ZnO refer to diammonium hydrogen phosphate and zinc oxide respectively.

Activity	**Gas**	**Emission factor**	**Unit**	**Reference**
Production of DAHP		8.938E-01	kg CO2e/kg	[25]
Production of formic acid		2.510E+00	kg CO2e/kg	[26]
Production of lauric acid		7.470E-01	kg CO2e/kg	[25]
Production of ZnO	CO_2	1.810E+00	kg CO_2/kg	[25]
	CH_4	1.690E-03	kg CH_4/kg	
	N_2O	1.110E-04	kg N_2O/kg	
Production of ammonia	CO_2	5.820E-01	kg CO_2/kg	[25]
	CH_4	5.820E-05	kg CH_4/kg	
	N_2O	3.670E-05	kg N_2O/kg	
Production of sulfuric acid	CO_2	5.200E-02	kg CO_2/kg	[25]
	CH_4	5.130E-05	kg CH_4/kg	
	N_2O	6.330E-06	kg N_2O/kg	
Production of Diesel	CO_2	1.230E-01	kg CO_2/l	[25]
	CH_4	8.970E-05	kg CH_4/l	
	N_2O	5.350E-05	kg N_2O/l	
Combustion of Diesel	CO_2	2.730E+00	kg CO_2/l	[25]
	CH_4	7.440E-05	kg CH_4/l	
	N_2O	4.440E-05	kg N_2O/l	
Generation of electricity (Sri Lanka)	CO_2	4.172E-01	kg CO_2/kWh	[27]
	CH_4	1.644E-05	kg CH_4/kWh	
	N_2O	3.288E-06	kg N_2O/kWh	

5.3.2.4. Definition of Material Flow Analysis (MFA)

The MFA is a systematic assessment of the flows and stocks of material within a system defined in space and time [28]. With MFA, it is possible to quantify mass flows of materials, stocks, outputs, and waste in a manufacturing system or a factory. MFA follows the mass balance principle; the input mass is equal to that of the output. After achieving the mass balance, the output is illustrated by a material flow model. This model can either be a simple input-output diagram or a Sankey diagram that visualizes flows in accordance with the flow rates of materials.

In this study, STAN 2.5 software was used for MFA calculations [29]. STAN 2.5 is a software that delivers a user-friendly graphical interface to conducting MFA. Though STAN 2.5 visualizes MFA model as a Sankey diagram, in view of providing a clearer version, Fig.2 had to be designed using e!Sankey software [30].

We conducted MFA of CL processing as follows. First, a material flow was constructed for each factory. Then, all material flows were integrated into one common material flow, where all flows were indicated using mean ± standard error (SE).

5.3.2.5. Definition of Material Flow Cost Accounting (MFCA)

MFCA is a tool, which aims to reduce both the environmental impact and costs of an organization through waste reduction [31]. MFCA turns material flows and stocks in a manufacturing process into monetary terms and provides information on monetary losses [32]. In other words, MFCA unveils the monetary loss attributed to each process in terms of numbers, thereby enabling the organization to identify its problems and recognize necessity for improvements.

MFCA considers four types of cost inputs for each processing unit (N.B. processing unit is called a quantity center (QC) in MFCA): 1) material cost, 2) system cost, 3) energy costs, and 4) waste management cost. It further categorizes each cost input into two groups at the output; positive product and negative product cost. Positive product cost is put on the product, whereas the negative product cost is the cost lost due to material losses and emissions. Material, system and energy costs falling into the negative or positive product cost category are always referred as negative or positive material, system and energy costs, respectively. Negative material, system and energy costs can be calculated multiplying input material, system, and energy costs by the percentage of material loss by weight. However, waste management cost is solely allocated to the negative product cost category.

Three types of materials are considered in MFCA; raw, auxiliary and operating materials [33]. Raw materials build up the final product. Auxiliary materials are the other materials that may end up in final product; whereas operating materials are essential to manufacture final product, but always end up as emissions and/or wastewater, in other words, non-product outputs (NPO).

MFCA for CL processing was conducted as follows. Firstly, we defined QCs according to the CL manufacturing flow. For simplicity, we combined transportation, unloading and bulking into one processing unit named as QC1 and labeled as `latex reception & bulking`. Similarly, coagulation, milling, drying, DBM and cutting, and packaging were integrated in QC4 and labeled as `skim processing`. Meanwhile, QC2 and 3 encapsulated the individual processes of centrifuging and preservation, respectively. Secondly, by following the allocation criteria explained in preceding paragraphs, an MFCA model was constructed for each factory on excel spreadsheets. Finally, all MFCA models were combined to get a common MFCA model representing CL manufacture in Sri Lanka. Entire MFCA was performed in Sri Lankan rupees (LKR) where LKR 1 = USD 0.006.

5.3.2.6. Definition of Life Cycle Assessment (LCA)

Environmental life cycle assessment is a tool which measures overall environmental burden of products and services across their walks of life to promote a better understanding of possible environmental impacts [34]. LCA of this study could be considered as a partial LCA as it was limited only to the manufacturing phase of CL and also to global warming potential (GWP). It was based on the principles and framework of ISO 14040:2006 [35]. Due to the lack of data on emission and conversion factors, our LCA has been confined to measuring GWP of GHGs incurred by CL manufacture. GWP was calculated either by following a GWP model in Jawjit et al. [2] or simply multiplying the conversion factor in kg CO2e per unit by level of activity. Initially, the data was compiled to appraise GWP per activity and net GWP in each factory. Calculated GWPs of each factory were then combined to determine average GWP per activity and net GWP of the CL manufacture.

5.3.3. Step 2: Proposal of Improvement Options

This step was conducted to pursue two objectives; 1. to identify key drivers of negative product cost and GWP impact, and 2. to propose applicable options addressing the identified drivers. To meet first objective, we deployed Pareto and What-if analyses, respectively. Pareto analysis is a tool for differentiating major causes of a problem from the minor ones [36]. It follows the Pareto`s 80/20 rule that expects 80% of effects come from 20% of causes. These 20% of causes are always identified by plotting a Pareto diagram. It comprises both bars and a line, where individual values are represented in descending order by bars while their cumulative total is marked by a line (for an illustration please refer to Fig. 5.4). Drawing a horizontal line starting from the 80% mark of y-axis, and then dropping that line at the point of intersection with the curve on the X-axis would separate the important causes (i.e., 20% of causes affecting 80% of effects) from the less important ones. Herein, a Pareto diagram for each factory was prepared identifying the important causes of respective negative product costs.

What-if/one-way sensitivity analysis allows assessing the impact caused by the changes in a certain parameter or a set of parameters on an output of a model [28]. Here, only one parameter or each in a set of parameters is changed at a time (i.e., 5% for this study) while keeping others at a constant. Changes in the model output were recorded, and ultimately presented as a tornado diagram (for an illustration please refer to Fig.5.5). In such a diagram, longer the bar greater the impact of a certain parameter on the model outputs. We prepared a tornado diagram for each factory for identifying the parameter/s with the highest impact on respective GWPs.

Second objective was achieved interviewing factory officials and owners, an electrical engineer and superintendent, and referring to literature.

5.3.4. Step 3: Improvement Potential Validation; a Scenario Analysis

Main objectives of this step were to evaluate degree of improvement (i.e., financial and environmental attributes) and efficiency bound with the nominated options. Since all options remained applicable in practical context, a combined scenario in which all options are applied (i.e., combined scenario) has also been taken into account. We deployed discounted cash flow analysis, GPBT, and developed novel `loss reduction efficiency index' in this regard. Our discounted cash flow analysis included Net Present Value (NPV) and Discounted Pay Back Time (DPBT) at 5.2% discount rate and then Internal Rate of Return (IRR). These indicators allow to normalize the time bound values of investments and returns considering the market flows, hence are typically used to evaluate investment decisions or projects as [37][38].

NPV calculates the difference between the present values of cash inflows and outflows over the life time of an investment or project [39]. Investment or project is considered worthwhile if NPV becomes positive. The equation used to calculate the NPV is as follows [40]: $NPV = \sum_{t=0}^{n} \frac{I_t - O_t}{(1+r)^t}$ where I_t and O_t are the expected cash inflow and outflow, respectively at particular time point (usually in years), r is the risk adjusted discount rate (in %) and t is the relevant time point (in years). Risk-adjusted discount rate was assumed 5.2% referring to the annual reports of central bank in Sri Lanka [41].

IRR refers to the discount rate at which NPV of an investment or project is zero [40], hence indicates the highest level of interest rate to be considered in borrowing or lending in an investment. The same equation for NPV is applied here with reverse estimation of r.

DPBT ascertains the period that it takes discounted net cash flows of an investment or project to break-even from an investment [42]. As for IRR, the same equation for NPV is applied for DPBT with reverse estimation of n.

GPBT is defined as number of years that it takes for an investment or project to payback its embodied GHG emissions through a particular option or options for GHG savings or GHG avoided per year [43]. GPBT is calculated according to the following equation [43]: $GPBT = \frac{kgCO2e_{embodied}}{kgCO2e_{avoided/year}}$ where $kgCO2e_{embodied}$ are the embodied emissions bound with a project, and $kgCO2e_{avoided/year}$ are the emissions avoided per year by a particular option or options to be adopted in the project.

Loss reduction efficiency (LRE) index was developed to provide a simple evaluation of the overall efficiency of a particular option or options in the project in terms of its economic loss and environmental impact reductions, DPBT, and GPBT. Also, LRE index facilitates to compare the performances amongst investments or options and to select the best; the option having the highest LRE index is considered best whereas the lowest is deemed worst. LRE index consists of economic and environmental components that define economic and environmental efficiency of an option, respectively. Economic efficiency is measured in terms of its importance relative to environmental efficiency, economic loss reduction and DPBT whereas environmental efficiency is gauged in terms of its importance relative to economic efficiency, environmental impact reduction and GPBT. Equation for LRE index is as follows.

$$LRE\ index = \frac{ax}{DPBT} + \frac{by}{GPBT}$$

Where a and b are relative importance of economic and environmental efficiency, respectively in terms of a fraction and therefore $a + b = 1$; x and y are economic loss reduction and environmental impact reduction fractions, respectively with the values between 0 and1; $DPBT$ is discounted payback time (in years); and $GPBT$ is greenhouse gas payback time (in years). To avoid 'divided by zero error' and ease the calculations, numerals for DPBT and GPBT are required to be rounded off to the next highest integer; for instance, a payback time that drops between 0 and 1 years is considered 1 year. Given all that, LRE index is set to vary between 0 and 1.

NPV, IRR, DPBT, GPBT and LRE index for individual options and combined scenario, per individual factory were calculated using excel spreadsheets (please refer to section 4.2 for more details on calculation procedure). In assessing LRE index, an equal importance was given to economic and environmental efficiency as per authors` discretion. Finally, individual indicators from three factories were combined to get mean ± SE value for each indicator.

5.4. Results

5.4.1. Results of Step 1 (Quantification of Material Flows, Economic Losses and GHG Emissions)

Fig. 5.2 illustrates the material flows of CL processing, in other words, the output of MFA. In addition to material flows energy inputs have also been included in Fig. 5.2. According to Fig. 5.2, 1 MT of dry rubber contains in 3,220 ± 115 kg of field latex which yields 1,460 ± 15 kg of CL (in wet weight) and 90.8 ± 10.3 kg of skim crepe (in dry weight). Field latex is washed away due to water-cleaning of bowser, bulking tank and centrifuge bowl incurring rubber losses of 6.4 ± 1.8 kg, 11.8 ± 3.3 kg and 4.2 ± 1.2 kg in dry weight, respectively. Using 1,011 ± 394 kg of water for cleansing skim crepe sheets had resulted in 1,162 kg ± 115 of wastewater at milling and 55.2 ± 19.6 kg of vapor at drying. All factories followed their very own standards adding chemicals; hence, their quantities as a whole resulted in large SEs. Chemicals such as DAHP and sulfuric or formic acid were used with the respective quantities of 13.8 ± 1.0 kg and 17.8 ± 2.0 kg, and eventually ended up in 5.3 ± 1.1 kg of sludge and 2,566 ± 404 kg of effluent (serum and wastewater), respectively. Electricity and diesel had produced 463 ± 142 MJ and 441 ± 46 MJ of energy required for machinery and bowser truck running respectively. Of all processes where electricity involved, centrifuging was the largest electrical energy consumer, which consumed ca. 59 % of total electrical energy.

Fig. 5.3 illustrates the MFCA cost flow of CL processing. Based on Fig. 5.3, monetary losses occur at QC 1, QC 2 and QC 4. In these monetary losses, negative material cost holds the largest proportion at every QC. Amongst all QCs, the highest negative material cost, LKR 5,292 ± 864, occurs at QC1 where field latex being washed away due to cleaning of bowser and bulking tank. This field latex wastage has also caused LKR 24 ± 5 of negative system cost and LKR 20 ± 6 of negative energy cost at QC1. The second largest monetary loss comprising LKR 2,734 ± 991 of negative material cost, LKR 32 ± 32 of negative system cost, LKR 6 ± 6 of negative energy cost and LKR 567 ± 150 waste management cost is from QC 4. Skim rubber loss occurred at coagulation stage in factory A was the main driver of the reported monetary loss. Factory A had no trap tank installed to recover uncoagulated rubber streaming out of coagulation tanks; hence, our field interviews with factory officials revealed that ca. 1% of the rubber ran into coagulation tanks had been wasted. Since factory A is the only factory that holds a raw material wastage at QC1, negative system and energy costs at QC4 were characterized by extremely high standard errors. Total negative product cost of the system was recorded ca. 4% of total cost of manufacture (LKR 234,572 ± 19,832) with a value of LKR 9,608 ± 1273.

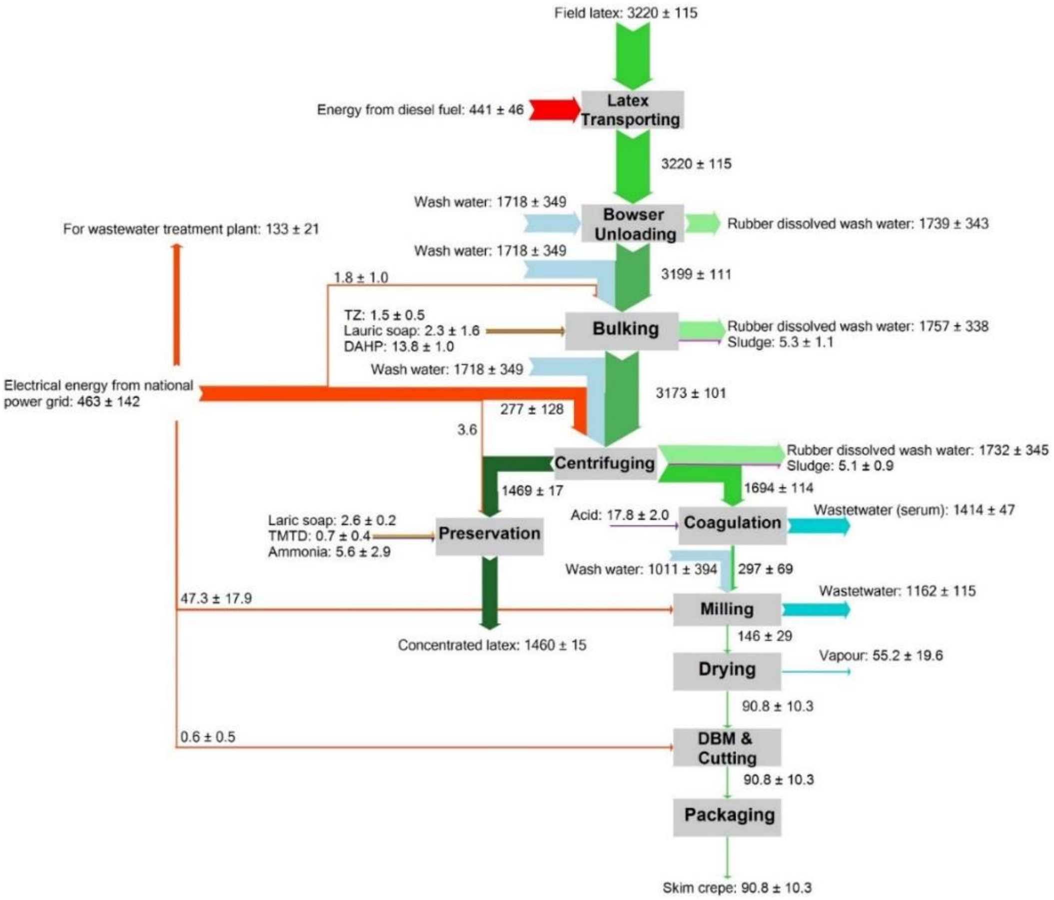

Fig. 5.2. Material flow analysis and energy inputs of concentrated latex manufacture per 1 MT of rubber input. All the values are denoted as mean ± standard error. Unit and color of energy inputs are MJ and red, respectively. Mass flows are represented by colors other than red whilst the values are given in kg. Codes DAHP, TZ, TMTD, and DBM refer to diammonium hydrogen phosphate, mixture of tetramethylthiuram disulfide and zinc oxide, tetramethylthiuram disulfide, and dry blanket milling, respectively.

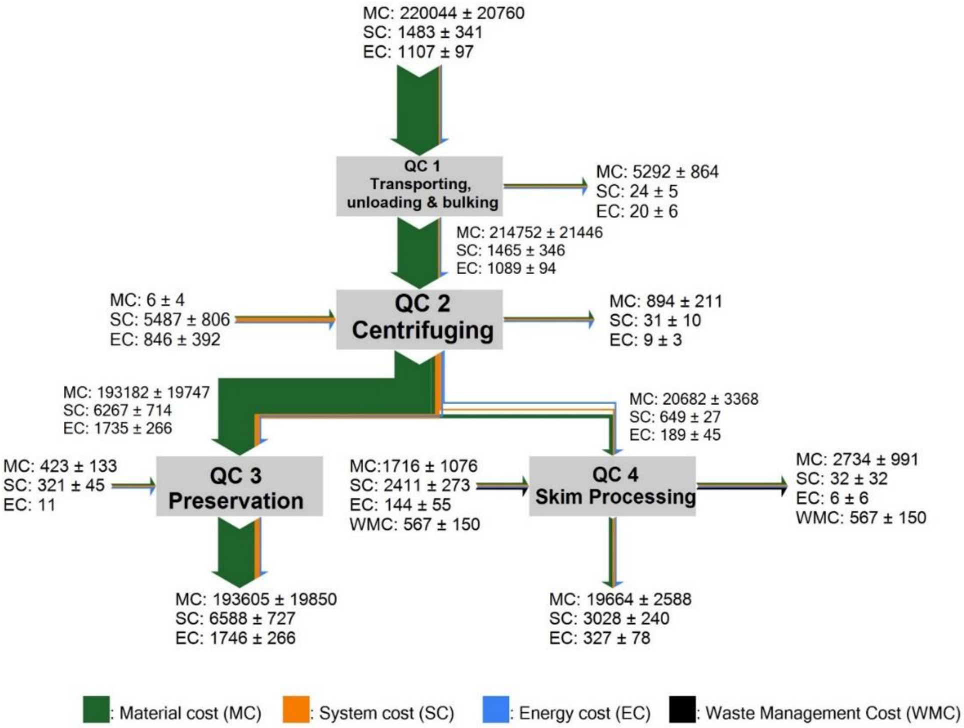

Fig. 5.3. Material flow cost accounting of concentrated latex manufacture. Cost flows are indicated in kg per 1 MT of rubber input. Codes QC, MC, SC, EC, and WMC refer to quantity center, material cost, system cost, energy cost, and waste management cost, respectively.

According to LCA, GWP impact of CL manufacture was recorded 112.8 ± 31.1 kg CO2e. Table 5.2 breaks down this GWP impact in terms of the activities carried out. Table 5.1 indicates that electricity consumption accounts for ca. 48% of total GWP with a value of 53.9 ± 16.5 kg CO2e and is the largest contributor to GWP. Diesel and acid use also account for considerable shares within total GWP, which are 29% and 16% respectively. However, uncertainties associated with chemical use remained greater as factories followed different standards and practices in adding chemicals. To be more specific, formic acid consumption in factory C has increased GWP attributed to acid use with a greater uncertainty, i.e., 18.5 ± 17.7 kg CO2e. However, contributions from other activities to GWP remained very less or negligible.

Table 5.2. Global warming potential (GWP) impact breakdown of CL manufacture as per activity. Codes DAHP and ZnO refer to diammonium hydrogen phosphate and zinc oxide, respectively.

Activity	GWP impact	% of total
Electricity use	53.9 ± 16.5	48
Diesel use	32.9 ± 3.5	29
Acid use	18.5 ± 17.7	16
DAHP use	4.0 ± 0.8	4
Ammonia use	2.2 ± 1.7	2
ZnO use	0.6 ± 0.3	1
Lauric acid use	0.6 ± 0.2	1
Total	112.8 ± 31.1	100

5.4.2. Results of Step 2 (Proposal of Improvement Options)

Fig. 5.4 represents the Pareto diagram for factory A. In a Pareto diagram, the factors falling within 80% of cumulative percentage are deemed most significant. Rubber loss at QC3, rubber and DAHP losses at QC1 had been the most significant in this regard. In case of factory B, rubber loss at QC2, rubber and DAHP losses at QC1 were the most significant. For factory C, significant factors remained as rubber and DAHP losses at QC1, and NPO at QC3. Subsequent interviews with factory officials revealed that factors such as rubber losses at QC1 and QC2 were less preventable as they incurred due to field latex being washed away during the general practices such as bowser, bulking tank and centrifuge bowl cleaning. NPO at QC3 in factory C had incurred due to the formic acid use in the particular factory. Factory C had taken this measure to avoid a sulfide odor from wastewater treatment plant during the use of sulfuric acid. Obnoxious odor from the treatment plant had created a community provocation during this period. However, our field Interviews and literature revealed sulfur odor could incur due to multiple factors, e.g., problem with wastewater treatment plant, excessive sulfuric added in factory, inefficient removal of ammonia prior to adding sulfuric, excessive ammonia added in plantations, etc. (Please see discussion section for more details). Therefore, we herein refrained from addressing NPO at QC3 in factory C.

Based on expertise of factory officials, and the existing literature, the following options were proposed for addressing rubber loss at QC3 in factory A and DAHP loss at QC1 in all factories.

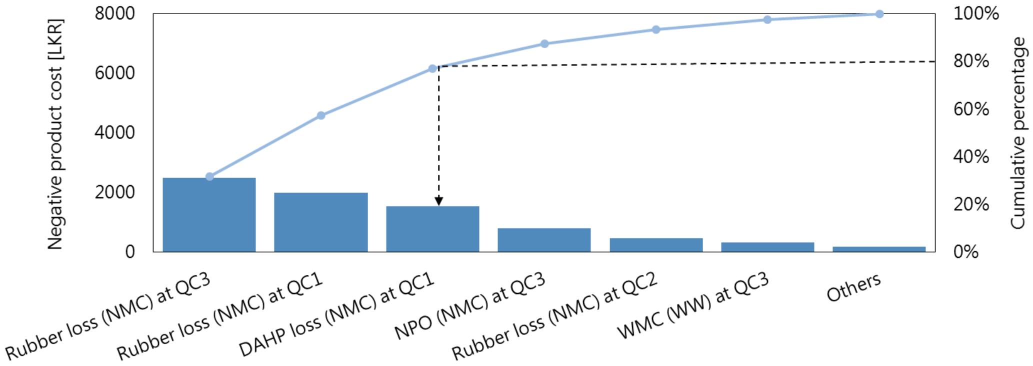

Fig. 5.4. Pareto analysis for factory A. Codes rubber loss (NMC) at QC3, rubber loss (NMC) QC1, DAHP loss (NMC) at QC1, NPO (NMC) at QC3, rubber loss at QC2, and WMC (WW) at QC3 refer to negative material cost occurred by rubber loss at quantity center 3, negative material cost occurred by rubber loss at quantity center 1, negative material cost occurred by diammonium hydrogen phosphate use at quantity center 1, negative product cost attributed to non-product outputs at quantity center 3, negative material cost occurred by rubber loss at quantity center 1, and waste management cost triggered by wastewater at quantity center 3, respectively. Please refer to section 5.3.2.5 for more information on quantity centers.

5.4.2.1. Installing Advanced Trap Tank to Factory A

Rubber loss at QC3 occurred due to the uncoagulated rubber particles streamed out with the serum at factory A. Uncoagulated rubber incurs due to the incomplete coagulation of skim rubber. Though this was a common issue in CL manufacture, trap tanks had been installed in factory B and C to recover this uncoagulated rubber. Comparably, the rubber trap facility in factory B was more sophisticated than that in factory C. This trap tank could coagulate 100% of the recovered rubber with no extra acid use by extending retention time of serum through partitioning of tank. According to the manager of factory B, extension of retention time allowed uncoagulated rubber particles to mingle with acid particles in serum to coagulate with no haste. In addition, the serum was air bubbled in order to remove ammonia for a fast coagulation.

Based on information from manager of factory B, a trap was designed to suite the daily amount of serum at factory A. Designing was carried out by a civil engineer. Amount of materials and capital cost were also estimated. Embodied emission factors required for GPBT were extracted referring to literature (reinforcing steel: 0.449 kg CO2e/kg [44], cement: 0.819 kg CO2e/kg [45], sand: 0.004 kg CO2e/kg [46], gravel: 0.01 kg CO2e/kg [46], roofing sheet: 2.284 kg CO2e/kg [44], structural steel: 1.802 kg CO2e/kg [44]). Lifetime of this project assumed 20 years.

5.4.2.2. Extending Sedimentation Time of Factory A, B and C

Mg^{2+} can enhance bacterial growth in field latex; hence, DAHP is used to sediment Mg^{2+} in the form of magnesium ammonium. Time period for this whole process is industrially referred as sedimentation time which was around 15 hours across all factories. However, extending this sedimentation time up to 20-24 hours can practically reduce

DAHP use by 10% [11][16]. Therefore, we herein propose all factories extend sedimentation time up to the said hours. Extra bulking tanks had been built in all factories; hence, we assume that any rush in manufacture caused by this option can be dealt with. Initial cost and lifetime of the project was assumed minimal (about zero) and 20 years, respectively.

Fig. 5.5 illustrates the tornado chart of What-if analysis conducted on factory B. Based on Fig. 5.5, diesel use is the most influential factor on GWP whilst electricity use being the second most influential. Hence, slight reductions in electricity and/or diesel use can notably reduce total GWP. The most and second most influential factors for factory A were electricity and diesel use respectively whereas those were electricity and formic acid use, respectively for factory C. However, minimizing diesel and formic acid use remained less feasible at the moment; thus reducing electricity was focused.

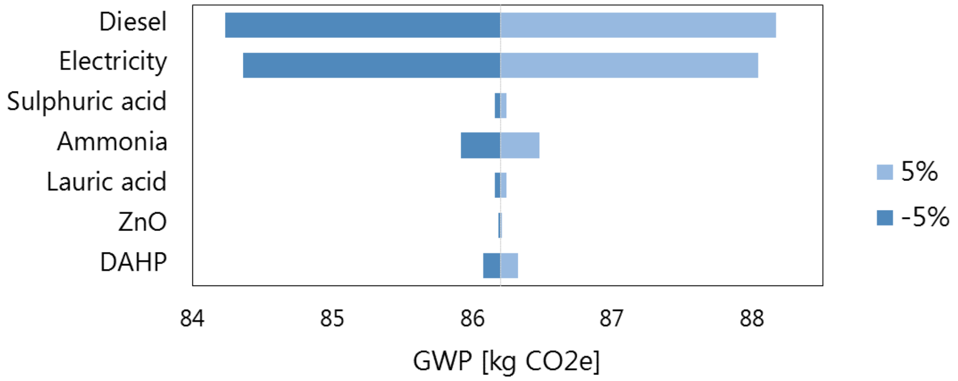

Fig. 5.5. Tornado diagram of what-if analysis for factory B. Codes GWP, DAHP and ZnO refer to global warming potential, diammonium hydrogen phosphate and zinc oxide. For more information on what-if analysis and tornado diagrams please see section 5.3.3.

5.4.2.3. Installing Inverters and Solar Panels to Factory A, B and C

Centrifuging had been recorded as the most electricity intensive process in CL manufacture and for which factory A, B and C used obsolete centrifugal machines with clutch and gear systems. Such systems tend to consume more electricity than other systems owing to inherited friction of clutch plates during start-up period [11][16]. Installing inverters has been effective in this regard as they gradually distribute electrical current to the machine until it catches up with the desired rotation, hence electricity loss during start-up is minimal. This practice can reduce electricity use by 10-12% [11][16]. Appropriate inverter capacities and installing costs were provided by an electrical superintendent, and inverter prices were known by contacting an inverter retailer in Sri Lanka. However, embodied GHG emissions of inverters had to be excluded from GPBT calculations as no emission factors were available. Lifetime of an inverter was assumed 5 years based on information provided by the contacted electrical superintendent.

Since all factories were located in tropical climate where plentiful of sunlight was available, installing solar panels was also proposed as a more effective electricity reduction option. Data on appropriate system capacities, cost per kW, roof area, tariff schemes and total project costs was obtained by contacting a company specialized in solar panels in Sri Lanka. Meanwhile, embodied GHG emissions of the systems were estimated based on 350 kg CO2e/m^2 of module area [47]. Twenty year lifetime was considered for solar systems. A scenario named `Combined Scenario` was also considered to foresee the improvement of CL manufacture when all options are applied.

5.4.3. Results of Step 3 (Improvement Potential Validation)

5.4.3.1. Option-1: Installing Advanced Trap Tank to Factory A

As per calculations, notable decreases in several negative cost segments were evident. For instance, total negative material cost had reduced from LKR 8,919 (SE 1,276) to LKR 8,149 (SE 1,697). In addition, total negative system cost had come down to LKR 55 (SE 15) from 87 (SE 19) whilst total negative energy cost had dropped to LKR 29 (SE 9) from LKR 35 (SE 3).These made total negative product cost per 1 MT rubber input reduce from LKR 9,608 (SE 1,273) to 8,802 (SE 1,912). But on the other hand, GWP per 1 MT of rubber input had increased from 112.8 (SE 31.1) to 113.0 (SE 31.0). NPV, IRR and DPBT of the project was recorded LKR 16,336,096, 333% and 0.3 years respectively. This option had increased GWP impact of CL manufacture, hence had indefinite or infinite GPBT. Since NPV > 0 and IRR> risk adjusted discount rate the project can be deemed profitable. But on the other hand, indefinite GPBT signifies less environmental friendliness of this option.

5.4.3.2. Option-2: Extending Sedimentation Time of Factory A, B and C

This option had mainly reduced negative material cost of CL manufacture, which per 1 MT rubber input had come down to LKR 8,771 (SE 1,254) from LKR 8,919 (SE 1,276). This had made total negative product cost decrease from LKR 9,608 (SE 1,273) to LKR 9,460 (SE 1,253). GWP per 1MT of rubber input had also reduced from 112.8 (SE 31.1) kg CO2e to 112.4 (SE 31.0) kg CO2e. Capital cost for the project was assumed minimal (in other words, zero), hence had no definite IRR. However, NPV was recorded LKR 2,745,440 (SE 1,375,352) whilst both DPBT and GPBT recorded 0 years. NPV > 0 claims that the project is profitable. Further, DPBT and GPBT= 0 indicates that economic and environmental benefits can be achieved from the very moment the option is deployed.

5.4.3.3. Option-3: Installing Inverters and Solar Panels to Factory A, B and C

This option could save 128.7 (SE 39.3) kWh of electricity (per 1 MT rubber input) originated from national power grid. This had made GWP per 1 MT rubber input come down by 53.9 (SE 16.4) kg CO2e (from 112.8 (SE 31.1) kg CO2e to 58.9 (SE 14.8)) kg CO2e accounting for ca. 48% reduction in total GWP. In addition to GWP reductions, total energy cost had reached zero whilst negative product cost had come down to LKR 9,187 (SE 1,269) from LKR 9,608 (SE 1,273). NPV, IRR, DPBT and GPBT of the project were recorded LKR 12,781,271 (SE 6,660,908), 10.6 (SE 2.2) %, 11.9 (SE 2.7) years and 3.6 (SE 0.1) years, respectively. NPV > 0 and IRR > risk adjusted discount rate claim that the project is profitable.

5.4.3.4. Combined Scenario (Applying all Options)

When all options are applied, negative product cost per 1 MT of rubber input of CL manufacture had gone down to LKR 8,231 (SE 1,877) from LKR 9,608 (SE 1,273) conferring a 14% decline. Furthermore, total input cost (total manufacturing cost) per 1 MT of rubber input had also declined from LKR 234,572 ± 19,832 to LKR 233,771 (SE 20,182). Drop in GWP impact per 1 MT of rubber input was 54.2 (SE 16.6) kg CO2e (from 112.8 (SE 31.1) kg CO2e to 58.6 (SE 14.7) kg CO2e), or was ca. 48%. NPV, IRR, DPBT and GPBT of the project were LKR 19,467,947 (SE 5,038,503), 20.3 (SE 6.3) %, 6.7 (SE 1.7) years and 3.7 (SE 0.1) years, respectively.

Fig. 5.6 encapsulates LRE indexes of individual options and combined scenario. Orange color of Fig. 5.6 represents economic efficiency whereas blue color signifies environmental efficiency of every option or combined scenario. It should be noted that LRE index for option-1 has not been averaged, and hence indicated as an individual case of factory A. Based on Fig. 5.6, Option-1 has the highest LRE index whilst combined scenario, option -3 and -2 hold the second and third highest and lowest indexes, respectively. However, Option-1 shows no environmental efficiency; hence, economically and environmentally efficient `combined scenario` remains ideal choice for improving CL manufacture.

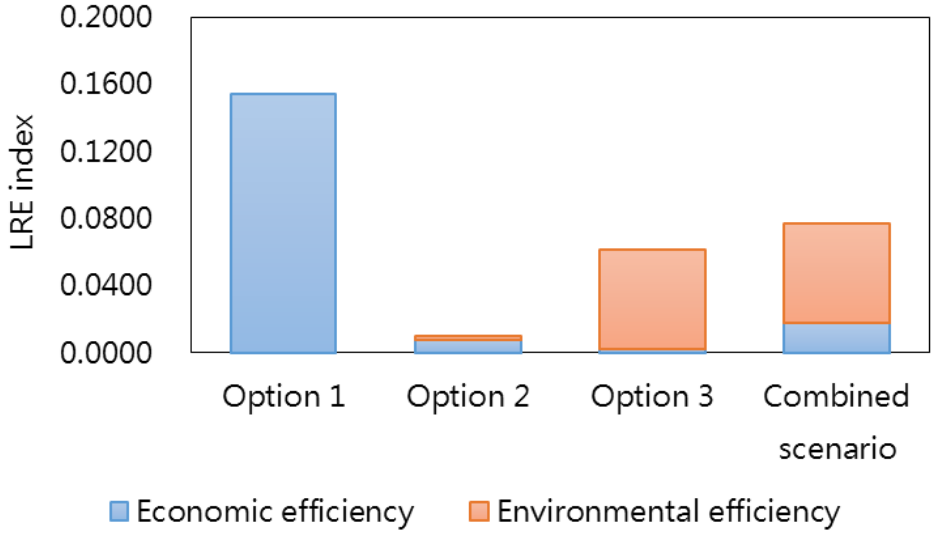

Fig. 5.6. Loss reduction efficiency (LRE) indexes of individual options and `combined scenario. `

5.5. Discussion

Overall, results indicated that the economic and environmental performances of current CL manufacture can substantially be upgraded by reducing most influential financial losses and GWP impact factors. Such reductions have saved dry rubber, DAHP and electricity savings in different stages of manufacture, resulting remarkable cost and GWP savings. All improvement options and `combined scenario` were proven to be profitable while only option-2,-3 and combined scenario remained environmentally viable.

As per LRE index, option-1, `installing advanced trap tank to factory A` had been the best out of all individual options and combined scenario considered herein. 100% recovery of rubber with less use of acid had been the main reason for this. However, option-1 gave no GWP reduction unlike other options and scenario; instead it had increased GWP impact by a certain level. This is because 100 % recovery of rubber had increased the amount of skim rubber (per 1 MT of rubber input) to be processed by machinery in factory A. Therefore, implementing second best `combined scenario` is a must for economic and environmental betterment of CL manufacture. On the way to combined scenario, implementing option-1 at first, secondly option-2 and lastly option-3 can be recommended from a viewpoint of rapid profits. For rapid environmental benefits, vice versa may be considered. Former is more likely to be preferred by managers from a developing country like Sri Lanka where profits are always prioritized.

In addition to direct benefits (i.e., reducing economic loss and GWP impact) indirect benefits of option-1,-2 and 3 exist. Option-1 lowers rubber particles, and sulfuric and ammonia concentration in serum; this lightens up the burden on wastewater treatment plant and prevents malodor problems. Toxicity of wastewater can be reduced by the chemical (i.e., DAHP) lowered through option-2 [48]. Less demand for primary fuel such as coal, gas and oil can be created by option-3 whilst reducing risks (e.g., contamination of environment by mining operations, drilling leaks and explosions, etc.) associated with their extraction [8].Whilst Sri Lankan government is trying to promote solar energy across the island through the project `battle for solar energy` [49], the findings herein would give further encouragement for CL or natural rubber factories to opt for solar energy. Indirect social benefits of these options can also be perceived. Attempts made by factories may create a positive public image toward factories at local level and help factories build healthy relationships with their local community. This may uplift the factories reputation along with its corporate image and which may later boost workers` morale toward team work and continuous improvement [50]. Moreover, number of customers will be proliferated.

Whilst literature on the economic aspect of CL manufacture being absent, several literature assessing environmental impact of which in Thailand and Indonesia has been published. GWP impact of CL manufacture in Thailand has been recorded 144 kg CO2e [2] and 169 kg CO2e [16] per ton of product whereas that in Indonesia was 436 kg CO2e [17] per ton of product. This value for CL manufacture in Sri Lanka when normalized to per ton CL (dry basis) becomes 128 kg CO2e which is somewhat and remarkably less than those for Thailand and Indonesia, respectively. These variations can be attributed to various manufacturing practices in these countries; for instance, CL manufacture in Thailand and Indonesia deployed diesel for drying process of skim block rubber whereas that in Sri Lanka used ambient air for drying skim crepe. However, electricity has been a decisive factor affecting GWP of CL manufacture in each country.

In a situation which the literature has been confined to partial analyses trying to address environmental or economic issues of CL manufacture, this study elaborates worthiness of integrating MFA MFCA, LCA, Pareto and What -if analyses, DCFA and GPBT in not only identifying real hotspots or issues in the manufacture but also appraising degree of improvement, financial and environmental returns in details. In addition to the said tools, LRE index integrated in the method proves to be beneficial in distinguishing highly efficient option/s from least efficient ones. Flexibility can be another feature of LRE index where weights given for economic and environmental importance can be altered as preferred. Multi criteria decision making tool such as analytic hierarchy process (AHP) can be used in this regard [51]. This structured technique organizes and analyses complex decisions using pairwise comparison approach to give more accurate order of priorities for decision making. AHP can easily be performed using a freely available software like `super decisions software` [51]. Further, one who is more interested in cost of manufacture than financial loss may consider reduction in cost of manufacture for LRE index. Illustration techniques used herein can also be used in CSR reports to render a crystal clear overview of the manufacture to readers [8].

Repetition of the method herein is recommended as it may reveal a new set of issues at each iteration. Addressing these issues may ensure continuous improvement in each individual factory and CL manufacture as a whole. Outcomes of each repetition can also be used for monitoring progress of the factory overtime and benchmarking it against the best in the market.

In addition to selected options, deployment of some other options may further improve CL manufacture. Loss of rubber content due to bowser, bulking and centrifuging cleaning can be lowered through re-centrifugation of rinse water from the first stages of cleaning [11]. Electricity can further be reduced by synchronizing motor start-ups to avoid peak loads, and installing new centrifuge machines [16]. This time we have refrained from addressing NPO at QC3 in factory C though it was identified as a most influential negative product cost factor for factory C (for more details please refer to section 5.2). Use of sulfuric acid instead formic acid of course lower the influence of this factor. However, to do so, curbing H_2S odor is a must. Minimizing sulfate concentration in wastewater may lower this odor by lowering activity of sulfate reducing bacteria in the wastewater treatment that produces H_2S [52]. Though this can be done through many methods, the most effective is to reduce sulfuric acid use in the manufacturing process [52]. Strict control of ammonia addition to fresh latex at between 0.4% and 0.5% to prevent high ammonia content in skim latex to reach PH 4.0-4.5 for coagulation and prevention of overdosing of sulfuric acid through continuous PH monitoring can be useful in this regard. These measures have reduced sulfuric acid use in Thai CL factories up to 200 kg per 1 MT of skim rubber with a minimal investment cost [52]. If applied to factory C, overall financial loss and GWP impact in CL manufacture can further be reduced by 11% and 16%, respectively. However, applicability of such to factory C is required to be scrutinized by a separate study, since transporting field latex from remote areas to factory C had required more ammonia than usual. Standard addition of ammonia in such cases may deteriorate the quality of CL. Through stirring of sulfuric with skim latex, use of deammonization tower, and long troughs leading to coagulation ponds are amongst other measures lowering sulfuric acid use. Treating wastewater with sodium hydroxide, aerating wastewater, use of sulfur reduction reactor (SRR) are other measures to eliminate H_2S odor [15]. SRR can further be combined with an up-flow anaerobic sludge blanket reactor (USAB) to produce quality biogas that can be used as a source of energy for factory operations [15]. Generating electricity using this biogas may reduce electricity demand in the factory whilst enabling spare electricity to be traded under net metering and net accounting systems in Sri Lanka; hence gaining extra revenue is possible. Diesel use has been another factor affecting GWP impact of CL manufacture and lowering of which was not scrutinized herein. Regular maintenance of engines, use of low emission vehicles, using biodiesel as fuel and improving load efficiency can be beneficial in reducing diesel use to make transportation of latex greener [12].Though not recognized as important, water use in CL manufacture can be reduced by regular supervision of water use, repairing or replacing leaky pipes, joints value and taps, using pressurized water guns, nozzles and automatic closing devices, and wastewater reuse [11].

Though audited factories had already made efforts toward sustainable manufacturing, barriers to such still exist. Limited expertise in sustainable or cleaner production practices and industrial process analytics, prioritizing profits and market share, high investment costs and requirement of additional infrastructure are some of them. Having a fear of losing market share, audited factories refrained from sharing successful manufacturing practices with fellow factories. Workshops on sustainable manufacture and industrial process analytics, governmental subsidies and incentives given to factories initiating sustainable manufacture, assembly sessions or use of social media for sharing status quo and successful practices of factories are some ways destroying the said barriers [8].

5.5.1. Limitations and Future Works

Not addressing social aspect of CL manufacture has been a major lacuna in the method herein. Therefore, future works may consider integrating social life cycle assessment (SLCA) in this regard. SLCA is a systematic assessment quantifying actual and potential social impact along the life cycle of a product which stretches from raw material extraction to disposal or recycling phase [53]. Inclusion of social aspect may force one to include social payback time (SPBT) in step 3 for a more advanced study. SPBT is a novel concept that can be explained as the duration that it takes for a project or investment to payback its negative social impacts through positive social impacts incurred per year. Integrating SLCA and SPBT could be extremely complicated, time consuming and may require lot of expertise, research and data. However, future work may consider adding these for not only for the sake of sustainability in manufacture but also as a contribution to research and development. Use of other midpoint impact categories (e.g., photochemical oxidation, ozone layer depletion, etc.) may reveal other environmental impacts of CL manufacture. Extending scope of this study to rubber plantations and even to value added rubber manufacture may also be considered by future studies. These attempts will not only ensure sustainability in natural rubber manufacture in the long run but also drag other industries in developing countries to the path of sustainability.

5.6. Conclusions

Main objective of this study is to uplift the cost efficiency and environmental friendliness associated with CL manufacture with use of a novel methodology. A case study of three CL factories in Sri Lanka has been conducted in this regard. Inefficient use of chemicals, energy, and dry rubber losses were mainly apparent as they resulted LKR 9,331 ± 1128 of financial loss and 113.1 ± 31.1 kg CO2e of GWP impact. Rubber loss of factory A, inefficient use of DAHP and electricity in all factories were identified as main drivers of monetary loss and GWP impact and installing advanced trap tank to factory A (option-1), extending sedimentation time of factory A, B and C (option-2), Installing inverters and solar panels to factory A, B and C (option-3) were proposed as improvement options. Determining financial loss and GWP impact reduction, economic and environmental returns, and novel LRE index for each option and `combined scenario` (applying option-1,-2 and -3) revealed `combined scenario` is the most efficient in terms of profits and environmental benefits. Financial and GWP impact reductions, NPV, IRR, DPBT and GPBT for this scenario were recorded 15%, 48%, LKR 19,462,135 (SE 5,067,198), 20.3 (SE 0.1) %, 6.7 (SE 1.7) and 3.7 (SE 0.1) years, respectively. Managers may implement the nominated options as the next step. For the sake of continuous improvement, they may repeat the method to identify new issues and use other options mentioned herein when required. These attempts would ultimately yield profits, increase in sales and lower toxic gases released into air. Moreover, uplifted factory reputation and working conditions are also perceivable.

Though barriers still exist, the method and findings herein can immensely be beneficial in reaching the ultimate target of sustainability not only in natural rubber industry but also in other industries based in developing countries.

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CHAPTER 6 Social Life Cycle Assessment in Raw Rubber Manufacture

6.1 Introduction

Raw rubber processing plays a major role in the rubber product manufacturing sector by providing raw rubber in the required form. Sri Lanka is one of the top rubber producing nations globally [1]. Also, it ranks as the seventh-largest exporter of rubber [2]. In Sri Lanka, rubber-based exports contributed 122,074 million Rupees (824 million USD) to the foreign exchange revenue in 2014 [1][3]. Moreover, this sector has offered 300,000 direct and indirect job opportunities to Sri Lankans [1]. Once latex is collected from rubber trees, it is processed into primary products referred to as raw rubber. This then is utilized in different manufacturing industries to be reprocessed into value-added rubber products. Raw rubber products such as crepe rubber, concentrated latex, and ribbed smoked sheets have been the principal raw material of many value-added rubber products such as pneumatic tires, surgical gloves, condoms, balloons, hoses, and so on [4].

Production of raw rubber is energy-, material-, and labor- intensive, where a significant amount of electrical energy, heat energy, fresh water, chemicals, and workforce are used at different stages of the manufacturing process [5]. Local community has closely bound to this sector as the majority of the workers and unwelcomed complaints on odor, water pollution, etc. are from the local community itself.

Raw rubber processing is currently confronted by low productivity, cost-ineffectiveness, and rising production costs, and various environmental and social issues [6][7]. To date, the environmental problems such as acidic wastewater discharge, malodor caused by rubber particles and chemicals, toxic smoke, and greenhouse gas emissions (GHG) have been reported [8][9]. Meanwhile, social issues such as deteriorated working conditions, low wages and social status, and pollution-bound community unrests are also evident [8][10][11].

Some studies have already been conducted to address above issues. Amongst them, Kudaligama et al. [12] and Siriwardena [13] tried introducing cost-effective wastewater treatment and drying facilities to raw rubber manufacture. Meanwhile, Jawjit et al. [14] and Jawjit et al. [15] focused on assessing and mitigating environmental impacts incurred by raw rubber manufacture using LCA-based approaches. Some water footprint-based studies are also observable with the purpose of evaluating and reducing freshwater consumption in raw rubber processing [16][17]. Our previous studies (i.e., Dunuwila et al. [18] and Dunuwila et al. [19]) had shed light on economic and environmental aspects of raw rubber manufacture by which we tried improving the cost efficiency and environmental friendliness of crepe rubber manufacture. Novel methods based on material flow analysis, material flow cost accounting and environmental life cycle assessment have been deployed in this regard. Though plenty of studies have shed light on economic and environmental aspects of raw rubber manufacture, studies touching the social aspect of raw rubber manufacture have been confined to simple social surveys of Bengtsen [10] and Nissanka [11].

Social life cycle assessment is popular tool that can be deployed to assess social dimension of a product or service. To be more specific, it is a systematic assessment that identifies key issues, assesses, and tells the story of social conditions in the production, use, and disposal of a product [20]. SLCA is still at its infancy and thus lacking a designated framework or methodology. Though have not so far been used in the raw rubber manufacture, novel methodologies have been developed for SLCA and deployed to assess social impacts of several manufacturing lines. All methods adopted Society of Environmental Toxicology and Chemistry/United Nations Environment Program (SETAC/UNEP) Code of Practice which rendered guidelines, and a set of subcategories, indicators and impact categories for SLCA of products [21]. Based on above Code of Practice, Manik et al. [22] proposed an SLCA framework to quantify social impacts incurred by palm oil production in Malaysia. Indicators were measured with use of a questionnaire based on a Seven-point Likert Scale. Here, the participants were requested to rank the indicators from 1 to 7, where 1 means unimportant and 7 means very important. These scores were then multiplied by the weight of each indicator for aggregating them to impact categories. Bork et al. [23] investigated furniture sector in Brazil with use of semi quantitative indicators where it used `yes` `and no` type questions for measuring them. No impact assessment had been conducted therein and instead indictors were simply aggregated to subcategories assuming equal weight for each indicator. Foolmaun et al. [24] tried knowing the social impact associated with polyethylene terephthalate (PET) bottle disposal in Mauritius. In this study, novel life cycle impact assessment method had been proposed for obtaining a single score for respective stakeholder category. This single score is achieved in three steps: 1) all indicator results were converted into percentages, 2) percentages were assigned to each subcategory based on a score ranging from 0 to 4; and 3) scores obtained in step 2 were summed up without no multiplication against any weighting factor. This impact assessment method had ability to suggest scores for the scenarios considered in that study. In view of comparing social performances associated with cutting roses in Netherlands to that in Ecuador, Franze et al. [25] deployed a color scheme ranging from very good performance to very poor performance. Both Inventory and impact assessment was based upon this color scheme. Same concept had been applied by Ciroth et al. [26] to knowing the social impact associated with Notebook manufacture. Based on a very own methodical hierarchy for SLCA, the social performances of Thai sugar industry had been investigated by Prasara et al. [27]. This hierarchy consisted of four steps: 1) screening process using social hotspot database (SHDB) to help identify process that are sensitive to the total social impacts of a product studied, 2) definition of functional unit and system boundary as per relevance and data availability, 3) selection of social subcategories and stakeholders involved based on SETAC/UNEP Code of Practice; and 4) impact assessment based following the concept in Manik et al. [22]. Indicators used in impact assessment took a form of `yes` and `no` type questions. Later the answers were converted into positive or negative percentages following the form of question. For subcategories having more than one indicator, average positive and negative percentages were used. For further interpretation, subcategories were rated from most important to less important based on the opinion of stakeholders. For instance, a subcategory having high percentage of importance and negative performance meant that this subcategory needed urgent improvements. On the other hand, one with high percentage of importance and positive performance deemed success of sugar industry in the development of social conditions. In attempt to analyzing the social impacts of different packaging waste collection systems, a new social life cycle assessment method had been considered and applied to eleven different waste collection scenarios centering Istanbul city, Turkey [28]. In this study, subcategorical indicators were assessed quantitatively and semi -quantitatively using the data collected from waste collectors. In latter stages, these indicators were converted into comparable scores ranging low (0), medium (0.5) and high (1). Therein, the lowest score showed the most positive impact whereas as the highest indicated vice versa. To allocate indicator results to subcategories, impact categories and total impacts, equal weighing was used. Meanwhile a methodical framework called subcategorical assessment method (SAM) had been formulated in assessing the social impact associated with Cocoa soap manufacture [29][30]. SAM is a characterization model that can be used at impact assessment phase of SLCA. SAM is based on a four-level scale (i.e., A, B, C or D) for each subcategory. Here each level holds a score; for instance, A is assigned a score of 4 whilst B, C and D are assigned scores of 3,2, and 1, respectively. Level A indicates that organization had a proactive behavior in promoting good social practice in the value chain. Level B is for an organization which fulfills basic requirements as the reference point or threshold (e.g., minimum wage level of a country). Levels C and D refer to the organizations which do not comply with the basic requirement. Assigning to these levels was based on social conditions of the country or sector; hence, SAM used SHDB. When such information was not available on SHDB, SAM extracted information from the organization itself. SAM had also been used by Lanzo et al. [31] to assess the social impacts incurred by a textile product manufactured in Sicily, Italy. Adding more rationality to the framework of SLCA, analytic hierarchical process (AHP; multicriteria decision-making tool that help organizing and analyzing complex decisions) had been integrated to life cycle impact assessment by several studies. For example, Hosseinijou et al. [32] did this in attempt to comparing the life cycle social impacts of concrete/cement to that of steel/iron in Iran. First, at inventory phase, this study Identified social hotspots in terms of the most important stages, stakeholders and subcategories in the life cycle of a building material. Then, at impact assessment phase, the identified hotspots were lined up to construct a hierarchy for pairwise comparison (N.B. pairwise comparison is the most important practice performed during AHP where two criteria are compared in terms of their relative importance. In denoting relative importance, a Likert scale from 1 to 9 is used. Single pairwise comparison is called a judgement). This pairwise comparison was performed by ten experts in manufacturing sector in Iran. With help of a model developed on MS excel, criteria weights and inconsistencies for each hierarchical level were calculated later on. This study aggregated subcategories to impact categories using scores of 1 and 0 where1 meant that there was connection between the subcategory and impact category whereas 0 denoted vice versa. Due to the lack of cause-effect chains of social impacts, this aggregation was based upon author`s thoughts.

One shortcoming of AHP is that pairwise comparison becomes extremely time-consuming as the hierarchy gets larger. In other words, number of judgements made during pairwise comparison skyrockets in such cases. To address this, consistent fuzzy reference relations (CFPR) method was proposed by Wang et al. [33]. This CPRF method reduced number of judgements to n-1 whilst traditional AHP considered n (n-1)/2 judgments for a hierarchical level with n elements. Wang et al. [34] leveraged this concept in attempt to knowing the social impact of workers in Taiwanese electronics sector. This AHP concept had been applied in other studies such as De Luca et al. [35] and Amrina et al. [36] for knowing social impact of citrus farming in southern Italy and cement manufacture in Indonesia, respectively.

Whilst no SLCA is performed in raw rubber manufacture to know its social impacts, literature on SLCA shows that there is no agreed social impact assessment method available in SLCA. Therefore, we try to measure social impacts of raw rubber manufacture in numerical terms for the first time in history with our very own method for SLCA. Unlike most of the SLCA methods in literature, the high rationality and simplicity can be given as the key features of the method herein. Also, it holds an ability to foresee the degree of improvement in the social dimension of raw rubber manufacture. This time, as a case study, we deployed our method to quantify social impacts of the workers in a crepe rubber factory in Sri Lanka. In the next section an overview of the crepe rubber process is presented, and the methodology is explained in section 6.3. Section 6.4 presents the results and discusses them. Finally, section 6.5 closes with conclusions.

6.2. Overview of Crepe Rubber manufacture

First, fresh rubber latex collected in the rubber fields by tapping is transported to a crepe rubber factory and is prepared for standardization. During the standardization, water and sodium bisulfite are added as a dilutant and preservative respectively where fractionation tends to occur afterwards. Fractionation is a partial coagulation where the yellow fraction of fresh rubber latex (ca. 10% of dry rubber mass) is coagulated after the addition of water and sodium bisulfite. After the extraction of the yellow portion, the fractioned latex, i.e., white fraction is passed to the coagulation tanks. At coagulation, formic acid, a bleaching agent, and more water are added. Then the coagulum is removed in cubical pieces for passing through a series of two roller mills (i.e., macerator, diamond roller, and smooth roller) to gain laces of rubber. During the milling, substantial amount of fresh water is used for cleansing rubber and cooling machinery. When the milling is finished, the sheets are sent to a drying tower where they are kept for 3 to 4 days for drying. The dried laces are then forwarded to the folding section where the laces are stacked and folded to get 25 kg mats. These are again sent through a macerator for pressing them to form blankets and which is called dry blanket milling. The blankets are later on trimmed into a broker-specified standard size and the packaging which includes visual grading, bundling and wrapping is carried out.

6.3. Materials and Methods

6.3.1. Goal, system boundary and functional unit definition

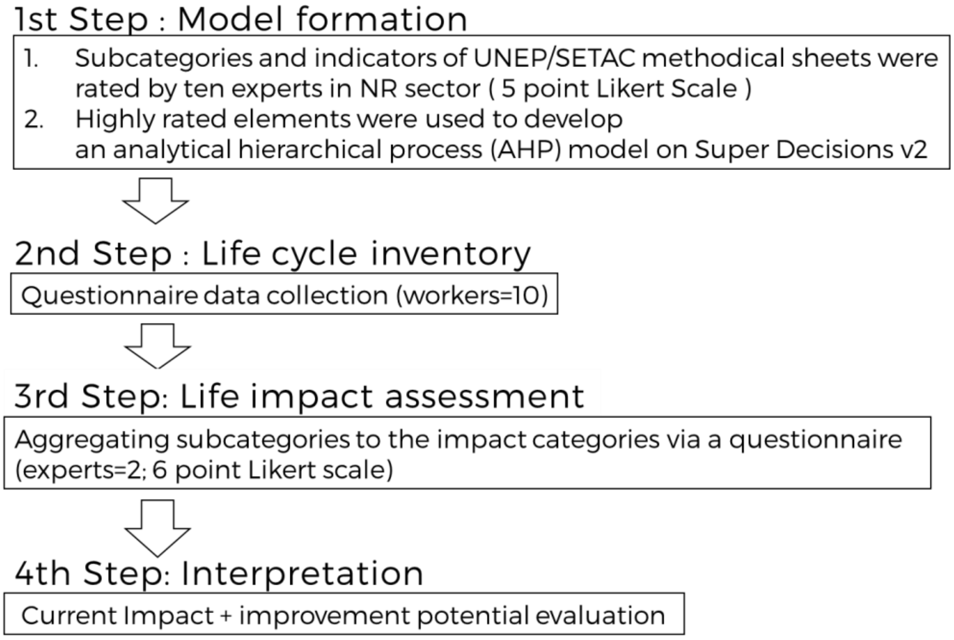
Our goal was to assess social impacts of crepe rubber manufacture in Sri Lanka with use of novel method for SLCA. System boundary was set to an in-factory assessment and a functional unit of 1 MT of dry rubber input was considered for all calculations.

6.3.2. Data Collection

Data were collected in one of the oldest crepe rubber factories in Sri Lanka via long-term field observations from April 2017 to June 2017. The factory had a production capacity of 500 kg rubber per day and employed 10 workers. Information necessary for SLCA was obtained from four surveys based on UNEP/SETAC Code of Practice [21]. Three surveys were answered by the experts in rubber industry while the rest were answered by the workers in the subjected factory.

6.3.3. Social Life Cycle Assessment

Fig. 6.1 illustrates the method proposed for SLCA. This method comprises of four basic steps: 1) construction of hierarchical model referring to UNEP/SETAC Code of Practice and expert opinions, 2) life cycle inventory based on a questionnaire survey for rating indicators 3) life cycle impact assessment for aggregating subcategories to impact categories; and 4) interpretation of results.



1. Subcategories and indicators of UNEP/SETAC methodical sheets were rated by ten experts in NR sector (5 point Likert Scale)
2. Highly rated elements were used to develop an analytical hierarchical process (AHP) model on Super Decisions v2

Questionnaire data collection (workers=10)

Aggregating subcategories to the impact categories via a questionnaire (experts=2; 6 point Likert scale)

Current Impact + improvement potential evaluation

Fig. 6.1. Methodical hierarchy of novel social life cycle assessment method proposed herein. UNEP/SETAC refers to United Nations Environment Program/ Society of Environmental Toxicology and Chemistry.

6.3.3.1. Step 1: Model formation

At this step, the subcategories and indicators listed under the stakeholder categories of workers, local community, society and value chain actors (in UNEP/SETAC Code of Practice) were rated by ten experts in rubber sector concerning their importance to natural rubber industry; Five-point Likert scale (1- Extremely important, 2 - Very important, 3 - Moderately important, 4 -Slightly important, and 5 - Not at all important) was used in this regard. In a case that a subcategory was measured by a single indicator, only the subcategory itself was rated neglecting its indicator. This time we only focused on measuring the social impact of workers; hence, the contents of the illustrations and tables herein have been adapted according to that. Table 6.1 summarizes the subcategories and indicators under workers considered for expert ratings.

Table 6.1 Subcatergories and indicators of workers considered for expert ratings.

Stakeholder	Subcategory	Indicator
Workers	Freedom of association and collective bargaining	Freedom to collective bargaining and joining unions
		Organizational support for unions
		Employee/union representatives are invited to contribute to planning of larger changes in the company, which will affect the working conditions
		Workers have access to a neutral, binding, and independent dispute resolution procedure
	Fair salary	Living/ Non-poverty Wages
		Existence of suspicious deductions on wages
		Presence of regular and documented payment of workers
	Hours of work	Working hours
		Presence of clear communication of working hours and overtime arrangements
		Organizational flexibility on scheduling
	Forced labor	Existence of forced labor
	Discrimination	Presence of discrimination

	Health and safety	Frequency of occupational accidents
		Satisfaction with formal policy concerning health and safety
		Satisfaction with occupational safety measures
		Satisfaction with emergency measures for accidents, injuries, and chemical exposure
	Social benefits/ social security	Social benefits and security provided

Ratings were geometrically averaged and a cut-off criterion was set at 3.00. Elements rated over 3.00 were used to construct an analytical hierarchical process (AHP) model on Super Decisions v2. AHP is a structured technique used in multiple-criteria decision making for organizing and analyzing complex decisions with respect to a pre-defined goal [37]. In this study, AHP is used to simplify the goal `Quantification of impact of raw rubber industry. ` In other words, AHP unveils the importance of each element (i.e., subcategories and indicators) with respect to a goal in a number which is called a global weight. Global weights are derived via pairwise comparison of the elements at each level of the hierarchy. Pairwise comparison in this study was based upon a Nine-point Likert scale (1- equal importance, 3- low importance, 5- moderate importance, 7- strong importance, very strong importance, and 2, 4, 8- intermediate values between two neighboring scales). The same ten experts took part in the pairwise comparison and later these ten pairwise matrices were geometrically averaged for gaining a combined pairwise matrix for constructing a common AHP model. Finally, the inconsistency ratios of each sub-criteria was checked for acceptability. In AHP, inconsistency ratio less than 0.1 is deemed acceptable [38].

6.3.3.2. Step 2: Life Cycle Inventory

Life cycle inventory was based on a questionnaire survey conducted on the workers of crepe rubber factory. To be more specific, our target herein was to get all indicators measuring subcategories rated by the workers in factory. All ten workers took in the factory part in answering the questionnaire. Though the questionnaire was prepared in English (Please refer to Table 6.2), lack of English language skills of the workers made us translate it to Sinhala prior to surveying.

Calculation procedure for this step was as follows. First, ten responses from ten experts for each indicator were geometrically averaged. Second, the averaged value for each indicator was multiplied with the global weight of corresponding indicator (in the common AHP model) to acquire an indicator score. Finally, these indicator scores were summed to acquire a subcategorical score for each subcategory.

Table 6.2 Questionnaire given to 10 workers of crepe rubber factory in Sri Lanka. Bold texts refer to the subcategories measured by the indictors underlined.

Freedom of Association and Collective Bargaining

Freedom to collective bargaining and joining unions

1= very good (no influence from any party to join & free to express any ideas)
2= good (no influence from any party to join & free to express only justifiable ideas
3= acceptable (no influence from any party to join & restricted freedom to express ideas
4= poor (some level of influence in joining unions)
5= very poor (not allowed to join unions)

Organizational support for unions

1= very good (provide financial support & duty leave for meetings)
2= good (no financial support but provide duty leave for meetings)
3= acceptable (no financial support but provide leave for meetings)
4= poor (no financial support & restricted leave for meetings)
5= very poor (no any financial support & no leave for meetings)

Employee/union representatives are invited to contribute to planning of larger changes in the company, which will affect the working conditions

1= they have always been invited to such occasions
2= they have invited to such occasions very often
3= they have sometimes been invited to such occasions
4= they have rarely been invited to such occasions
5= they have never been invited to such occasions

Workers have access to a neutral, binding, and independent dispute resolution procedure

1= there is no any intervention of management to the dispute resolution
2= rarely, there is an intervention of management to the dispute resolution
3= sometimes, there is an intervention of management to the dispute resolution
4= management very often intervenes the dispute resolution
5= management always intervenes the dispute resolution

Fair salary
Living /Non-poverty wages
5= less than 5,000 LKR per month
4= 10,000-5,000 LKR per month
3= about 10,000 LKR per month
2= 10,000-15,000 LKR per month
1= over 15,000 LKR per month
Suspicious deductions on wages
5= suspicious deductions are always evident
4= suspicious deductions are very often evident
3= suspicious deductions are sometimes evident
2= suspicious deductions are rarely evident
1= never came across with such deductions
Regular and documented payment of workers
1= regular payments with pay sheets
2= regular payment without pay sheets
3= delayed payments with pay sheets
4= delayed payments without pay sheets
5= no guaranteed payments

Hours of work
Working hours
1= occupational hours of work are <45 per week
2= occupational hours of work are >=45 hours and <=48
3= occupational hours of work are sometimes >=48 hours a week, and an overtime is paid
4= occupational hours of work are always >=48 hours a week, and an overtime is paid
5= occupational hours of work are always >=48 hours a week, and overtime is not paid
Clear communication of working hours and overtime arrangements
1= management provides the schedule in a monthly basis
2= management provides the schedule in a two-week basis
3= management provides the schedule in a weekly basis
4= management provides the schedule in a daily basis (the next day`s schedule is

provided on the very previous day) 5= management provides the daily schedule at the beginning of the day itself Organizational flexibility on scheduling 1= very good (schedules are always adjusted according to workers` preferences) 2= good (schedules are usually adjusted according to workers` preferences) 3= acceptable (schedules are sometimes adjusted according to worker`s preferences) 4= poor (schedules are rarely adjusted over workers` preferences) 5= very poor (workers are forced to work as their preferences are completely neglected)
Discrimination Presence of discrimination based on age, race, sex, religion, political association, and ethnic origin 5= workers have always been discriminated based on at least one of the factors above 4= workers have very often been discriminated based on at least one of the factors above 3= workers have sometimes been discriminated based on at least one of the factors above 2= workers have rarely been discriminated based on at least one of the factors above. 1= workers have never been discriminated
Health and safety Frequency of occupational accidents 5= always (once a week) 4= very often (once a month) 3= sometimes (once a year) 2= rarely (once a five year period) 1= never happened Satisfaction with formal policy concerning health and safety 5= no idea of formal policy concerning health and safety 4= understand or heard about the formal policy, and not satisfied 3= understand or heard about the formal policy, and slightly satisfied 2= understand or heard about the formal policy, and moderately satisfied 1= understand or heard about the formal policy, and satisfied over the expected level

Satisfaction with occupational safety measures 5= not at all satisfied (not available and operations are done at own risk) 4= slightly satisfied (not available but the management provides some safety supervision) 3= moderately satisfied (available but not adopted) 2= very satisfied (not a must but always adopted under the management`s supervision) 1= extremely satisfied (adoption is a must) Satisfaction with emergency measures for accidents, injuries, and chemical exposure (emergency washing facilities, first-aid facilities, an emergency telephone, fire extinguishers, frequent safety inspection, etc.) 5= not at all satisfied (none of the above is provided) 4= slightly satisfied (at least one or two of the above is available) 3= moderately satisfied (at least three of the above are available) 2= very satisfied (at least four or five of the above are available) 1= extremely satisfied (more than five measures are available)
Social Benefit/Social Security Satisfaction with social benefits (medical insurances, dental insurance, medicine insurance, wage insurance, paid maternity and paternity leave, education and training, paid sick leave, etc.) and social security (survivor’s benefits, etc.) 5= not at all satisfied (none of the above is provided) 4= slightly satisfied (at least one of the above is available) 3= moderately satisfied (at least two of the above are available) 2= very satisfied (at least three of the above are available) 1= extremely satisfied (four or more of the above measures are available)

6.3.3.3. Step 3: Life Cycle Impact Assessment

In this step, we aggregated the subcategories to six impact categories (i.e., human rights, working conditions, health and safety, development of the country, socio-economic repercussions and governance) included in UNEP/SETAC Code of Practice. Since SLCA is still at its infancy, the cause-effect chains between these subcategories and impact categories are still non-existing [32]. Therefore, this aggregation was based on the thoughts of two experts. Experts were asked to use six-point Likert scale (1- no impact, 2- very low impact, 3-low impact, 4-moderate impact, 5 - high impact, 6 - very high impact) for answering. Table 6.3 demonstrates the mark sheet given to experts. For example, if the expert thinks that the subcategory` Freedom of association and collective bargaining` has a very high impact on human rights of the country or area, he or she may put 6 at the intersection of `Freedom of association and collective bargaining` and `Human rights. ` Reponses from two experts were geometrically averaged and multiplied with corresponding subcategorical scores to acquire impact scores at the intersections where subcategories meet impact categories in the mark sheet. Finally, impact scores on each column were summed to get a total impact score for each impact category.

6.3.3.4. Step 4: Interpretation

The goal of this step was three-fold: 1) to comprehend and discuss current social impacts of the crepe rubber factory, 2) to identify social hotspots and propose countermeasures; and 3) to foresee the benefits of the proposed measures. No. 1 was done closely examining the results of life cycle inventory and impact assessment whilst no. 2 and 3 were implemented referring to literature and re-execution of step 2 (i.e., life cycle inventory) and 3 (i.e., life cyecle impact assesment), respectively.

Table 6.3 Mark sheet given to experts for aggregating subcategories to impact categories.

Stakeholders	**Subcategories**	**Impact categories**					
		Human rights	Working conditions	Health and safety	Development of the country	Socio-economic repercussions	Governance
Workers	Freedom of association and collective bargaining						
	Fair salary						
	Hours of work						
	Discrimination						
	Health and safety						
	Social benefits/ social security						

6.4. Results and Discussion

6.4.1. Results of Step 1 (Model Formation)

Table 6.4 encapsulates the mean importance values of subcategories and indicators listed under workers. According to the mean importance values, the subcategory `forced labor`, the mean value of which was less than 3.00, had to be eliminated. The refined model was then built on the interface of super decisions v2 software for AHP. Global weights achieved for each subcategory and indicator using AHP are as in Table 6.5.

According to Table 6.5, `Fair Salary` has been given the highest priority by experts. In addition, health and safety`, `social benefit/social security` and `hours of work`, ` ranked second, third and fourth in priority.

Table 6.4 Mean importance values of subcategories and indicators under workers. N/A refers to not applicable.

Stakeholder	Subcategory	Indicator
Workers	Freedom of association and collective bargaining (4.44)	Freedom to collective bargaining and joining unions (4.16)
		Organizational support for unions (4.00)
		Employee/union representatives are invited to contribute to planning of larger changes in the company, which will affect the working conditions (3.99)
		Workers have access to a neutral, binding, and independent dispute resolution procedure (3.57)
	Fair salary (4.78)	Living/ Non-poverty Wages (5.00)
		Existence of suspicious deductions on wages (3.71)
		Presence of regular and documented payment of workers (4.08)
	Hours of work (4.47)	Working hours (4.54)
		Presence of clear communication of working hours and overtime arrangements (4.16)
		Organizational flexibility on scheduling (3.62)
	Forced labor (2.75)	Existence of forced labor (N/A)
	Discrimination (3.44)	Presence of discrimination (N/A)
	Health and safety (4.65)	Frequency of occupational accidents (4.05)
		Satisfaction with formal policy concerning health and safety (3.92)
		Satisfaction with occupational safety measures (3.73)
		Satisfaction with emergency measures for accidents, injuries, and chemical exposure (4.04)

	Social benefits/ social security (4.57)	Social benefits and security provided (N/A)

Table 6.5 Global weights acquired for subcategories and indicators under workers.

		Weight
Subcategories of workers	➢ Freedom of association and collective bargaining	0.05033
	➢ Fair salary	0.14464
	➢ Hours of work	0.08629
	➢ Discrimination	0.01897
	➢ Health and safety	0.09945
	➢ Social benefits/ social security	0.08586
Freedom of association and collective bargaining	➢ Freedom to collective bargaining and joining unions	0.01327
	➢ Organizational support for unions	0.00790
	➢ Employee/union representatives are invited to contribute to planning of larger changes in the company, which will affect the working conditions	0.01181
	➢ Workers have access to a neutral, binding, and independent dispute resolution procedure	0.01734
Fair salary	➢ Living/ Non-poverty wages	0.06294
	➢ Existence of suspicious deductions on wages	0.02026
	➢ Presence of Regular and documented payment of workers	0.06143
Hours of work	➢ Working hours	0.03130
	➢ Presence of clear communication of working hours and overtime arrangements	0.02711
	➢ Organizational flexibility on scheduling	0.02788
Discrimination	➢ Presence of discrimination based on age, race, sex, religion, political association, and ethnic origin	0.01897
Health and safety	➢ Frequency of occupational accidents	0.00992
	➢ Satisfaction with formal policy concerning health and safety	0.01746
	➢ Satisfaction with occupational safety measures	0.03663
	➢ Satisfaction with emergency measures for accidents, injuries, and chemical exposure	0.03544
Social benefits/ social security	➢ Satisfaction with social benefits and social security	0.08586

6.4.2. Results of Step 2 (Life Cycle Inventory)

Fig 6.2 demonstrates the social life cycle inventory (subcategorical impacts) in the form of a bar chart. According to Fig. 6.2, `social benefit/ social security` and `health and safety` of the factory are the most affected with the scores of 0.4198 and 0.3924, respectively. In addition, `hours of work` and `fair salary` have fairly been affected at 0.3263 and 0.3006, respectively. However, the least affected is that the ‘discrimination`. These findings will explicitly be discussed in section 6.4.4.

6.4.3. Results of Step 3 (Life Cycle Impact Assessment)

Fig. 6.3 depicts the outcome of social life cycle impact assessment. As per Fig. 6.3, the greatest threat is at the `working conditions` of the country or area with a score of 8.4751. Meanwhile, the second and third greatest threats are at the `health and safety` and `human rights`. However, results indicate that the socio-economic repercussions of the country or area are the least likely to be affected. Detailed explanations on these findings are presented in the next section.

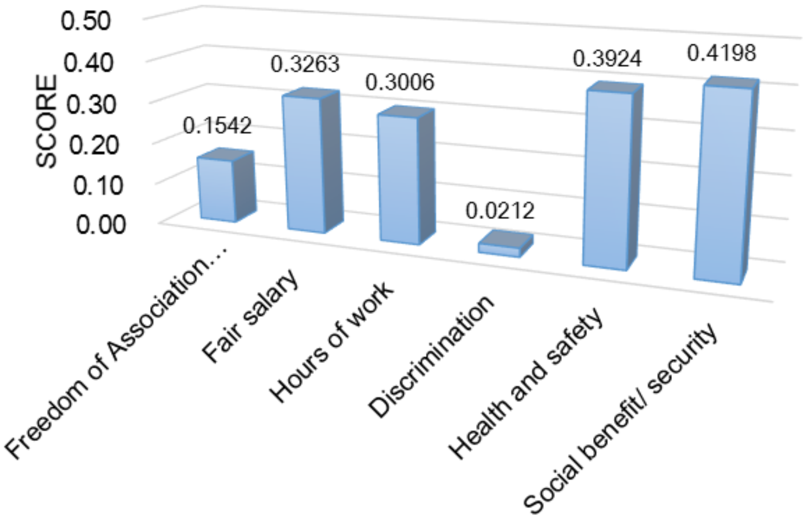


Fig. 6.2. Social life cycle inventory (subcategorical impacts). Score here refers to subcategorical score.

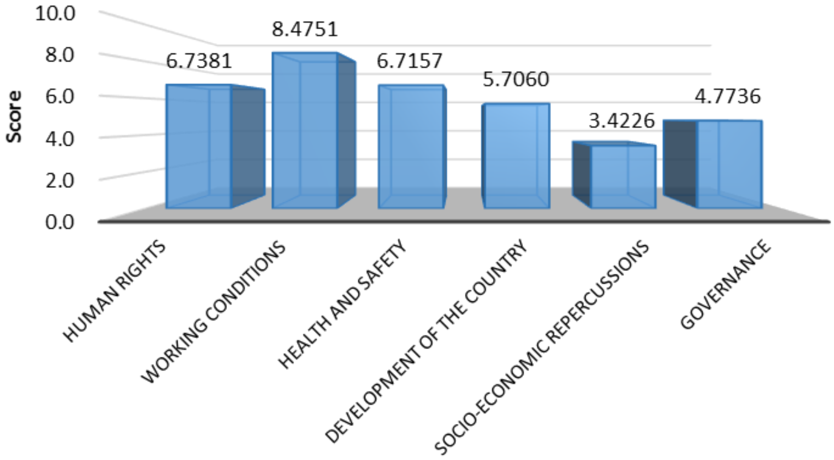


Fig. 6.3. Social life cycle impact assessment. Score here refers to impact categorical score.

6.4.4. Results of Step 4 (Interpretation)

The ‘health and safety’ and ‘social benefit/security’ were found to be the most affected as per life cycle inventory. It was apparent that above subcategories ended up deteriorating the working conditions of the country or area mainly. ‘social benefit/security’ was affected because workers had no insurance plan what so ever though they had to do a risky job operating rollers, handling toxic chemicals (e.g., formic acid, bleaching agents, sodium bisulfite, etc.), and lifting heavy rubber bulks and sheets. Meanwhile, the health and safety standards had mainly been affected by the absence of occupational safety and emergency measures. No safety measures were followed at the factory, and no safety equipment was provided. Workers had to work at their own risk. Besides, interviewed workers had no idea or satisfaction about the formal policy concerning health and safety. Interviewees revealed that if injured, the patient would be sent to a factory doctor, and then simply be released. If only the accident is serious, an arbitrary transportation is provided to take the patient to the hospital. As no paid sick leaves or insurance were available, the patient would have to work even though they were not in a perfect fit. In such cases, the only relief was that the injured worker was assigned a simple work.

In order to improve social conditions, the following scenario is considered. Medical insurance is provided. Moreover, employees’ health and safety had been ensured by providing occupational safety precautions (e.g., provision of protective gear, proper storage of chemicals, shovel and buckets for chemical handling, education, and training, etc.), and emergency measures (e.g., emergency washing facilities, first-aid facilities, an emergency telephone, fire extinguishers, frequent safety inspection) [39][40]. Furthermore, the management supervises the adoption of such precautions while disseminating the company`s formal policy on health and safety to workers. For the re-execution of life cycle inventory, we assumed that the accident rate stayed the same and workers held a clear idea of a formal policy on health and safety and were moderately satisfied.

Fig. 6.4 illustrates the reductions of sub-categorical impacts as per the scenario proposed. According to Fig. 6.4, the changes in `health and safety` and `social benefits/social security` were about 62% and 18%, respectively. Fig. 6.5 illustrates the reductions in impact categorical impacts where significant changes can be seen in all impact categories. It shows that impacts on health and safety, development of the country, socio economic repercussions, working conditions, governance and human rights have significantly been minimized by 27%, 24%, 17%, 19%, 20% and 16%, respectively. Overall, these results show the betterment of factory’s social aspect.

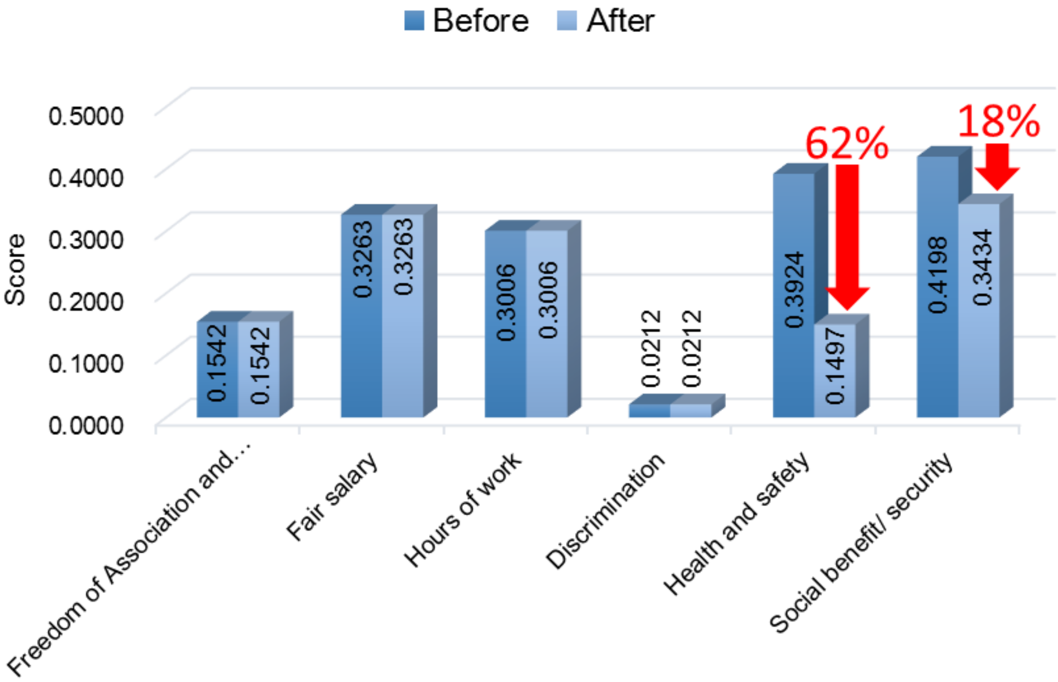


Fig. 6.4. Subcategorical impact reductions. Score here refers to impact categorical score.

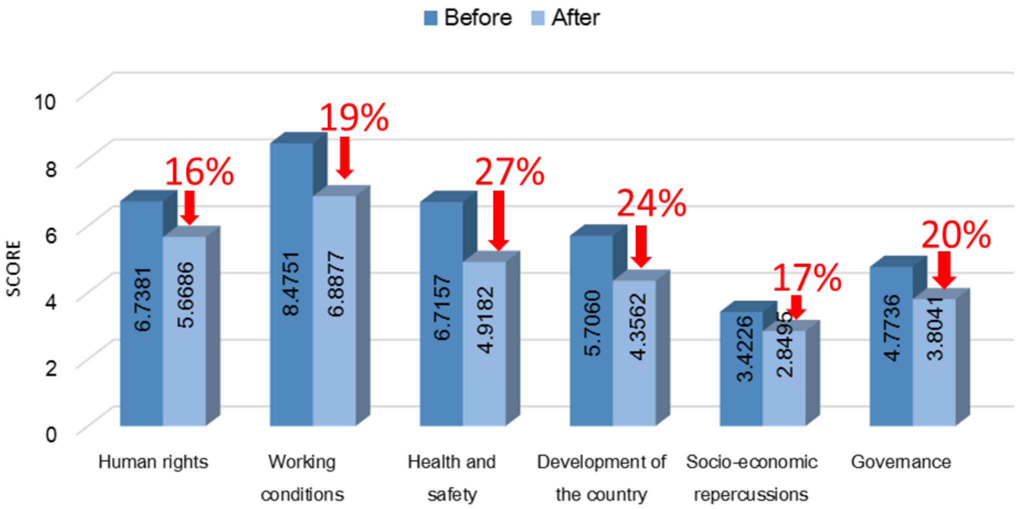


Fig. 6.5. Impact categorical reductions. Score here refers to impact categorical score.

Low wage is a major issue amongst the estate workers in Indonesia [10] and the Sri Lankan estate sector is no exception to that [41]. According to our findings, the wage (described as fair salary) ranked third in the inventory. This happens because we regarded the minimum wage in Sri Lanka (10,000/ month LKR [42]) as the base for fair salary. If the living wage, 48,000 LKR [43], is considered instead of the minimum wage, the outcomes of SLCA would have been slightly different.

However, Tillekeratne [40] supports our inventory results as it claims health and safety of raw rubber factory workers in Sri Lanka is in danger. To the best of our knowledge, none of the literature reports the social benefits and security of estate or raw rubber factory workers. Therefore, the revelation of the endangered social benefit/security conditions of raw rubber factory workers can be given as a major finding of this work. Our interviews with the experts revealed that such benefits were not provided in many cases due to financial reasons and temporary contracts. Furthermore, step 4 proved that the betterment of social security and health and safety was a must for bettering social conditions in the country or area as a whole. Provision of good health care and security to workers may boost the factory reputation whilst building a positive public image toward the factory. Uplifted factory reputation can further boost workers morale by fostering teamwork and continuous improvement, thereby leading to remarkable improvements in working conditions [44]. We believe that low level of discrimination prevailed within the factory may accelerate the preceding phenomena.

This time, measuring social impact of workers had been the sole focus; hence, future works should try to quantify the social impacts of other stakeholders (i.e., Local community, society, and value chain actors) in raw rubber manufacture with use of novel method introduced herein. We believe that any industry can adapt our SLCA methodology by giving simple modifications to it. For instance, one may add more indicators and subcategories to the method referring to UNEP/SETAC code of practice and interview greater number of experts for more accurate decision-making. Nevertheless, high-level of subjectivity and requirement of great deal of expertise and data can be given as shortcomings of the introduced method. In generalizing the findings herein to entire raw rubber manufacture, several factories will have to be investigated using the same method.

6.5. Conclusions

A comprehensive social assessment had been absent in raw rubber manufacture and thus social impact incurred by which had been unknown so far. In order to fill this gap, this study applied a popular tool dedicated for assessing social impacts, SLCA, to raw rubber manufacture for the first time in history. On top of that, amidst there is no designated method for SLCA, this study formulates a novel method which is simpler and more rational compared to the SLCA methods published in literature. In view of conducting a case study, crepe rubber factory in Sri Lanka had been subjected to this study. Results indicated that social benefits/ social security, and health and safety of the workers had greatly been threatened. Moreover, this had significantly deteriorated the working conditions, and health and safety of the country or area as well. Therefore, countermeasures proposed were found bettering `health and safety` and `social benefits/security` by 62% and 18% respectively. Also, such betterments have resulted improving the health and safety, development of the country, socio economic repercussions, working conditions, governance and human rights in country or area by 27%, 24%, 17%, 19%, 20% and 16%, respectively. Therefore, responsible officials should take immediate steps to realize the countermeasures discussed herein to uplift social sustainability in the factory. Quantifying only the social impacts of workers can be given as a major limitation of this study; hence Impacts of other stakeholders (i.e., local community, society and value chain actors) should also be assessed and comprehended by future studies. Furthermore, several raw rubber factories will have to be investigated in order to generalize the findings of this chapter. These attempts will reveal more interesting facts about social dimension of raw rubber manufacture that had buried for decades.

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CHAPTER 7 General Conclusions

This study entailed the three pillars of sustainability (i.e., economic, environmental and social) in raw rubber manufacturing sector for the first time in history in view of finding avenues for improving cost efficiency, environmental and social well-being. Raw rubber manufacture in Sri Lanka was subjected and four novel methods had been used in this regard.

Financial and environmental aspects of crepe rubber and ribbed smoked sheet manufacture were investigated with use of first method. This method comprised of three steps: 1) analysis of current manufacturing situation with use of material flow analysis (MFA), material flow cost accounting (MFCA) and environmental life cycle assessment (ELCA), 2) development of improvement options based on Pareto and what-if analyses, information from field interviews and literature; and 3) validation of improvement options in step 2 by re-executing MFA, MFCA and ELCA, and simple cost benefit analysis. Crepe rubber manufacture indicated inefficient use of chemicals water and electricity resulting LKR (Sri Lankan Rupees) 19,585 and 279.3 kg CO2e of financial loses and greenhouse gas (GHG) emissions, respectively. Improvement options proposed could reduce water and electricity consumption by substantial amounts thereby alleviating financial loss by 4.5% and GHG emissions by 1.1%. As regards RSS manufacture, waste was found to be very less; hence resulted in negligible amount of financial loss. However, GHG emissions were recorded 38.0 kg CO2e due to inefficient use of firewood for smoke-drying process. The efficient smoke house proposed as an improvement option could not only curb GHG emissions by 14% but also cost of production by 0.1%.

We tried to further improve financial and environmental sustainability of crepe rubber manufacture deploying our second novel method which was a derivative of the first method. Second method was based on the concept of continuous improvement as it tendered a practical and concrete framework for zeroing waste and emissions in time to come. Deployment of this method to a crepe rubber factory in Sri Lanka revealed that financial loss and GHG emissions of the factory could be reduced by 26% and 79% respectively in practical context.

A lacuna existed as both previous methods were less informative in analyzing feasibility of improvement options; Hence, simple cost benefit analysis was replaced by discounted cash flow analysis (DCFA), greenhouse gas payback time (GPBT) and novel loss reduction efficiency (LRE) index to formulating a third novel method presenting a comprehensive feasibility assessment of improvement options. This time concentrated latex manufacture had been subjected to the application of third method. CL manufacture was found to be affected by raw material losses, inefficient use of chemicals and electricity incurring LKR 9,331 and 113.1 kg CO2e of financial loss and GHG emissions, respectively. Results were promising as significant proportions of financial loss and GHG emissions could be lowered by the improvement options proposed therein; For instance, combined application of all improvement options could reduce financial and GHG emissions by 14%

and 48%, respectively while being financially and environmentally viable. Whilst overall approach adopted in this study demonstrated a unique model for redesigning processes, development of LRE index furnished a novel and simple way to assess the efficiencies of improvement options in indefinite dimensions.

Not evaluating social dimension of raw rubber manufacture had been neglected by all three methods; hence, performing a social life cycle assessment was the focus of our next attempt. Since SLCA lacked a designated method, our own method (i.e., forth method) was used therein. Quantifiability of both negative and positive social impacts, and foreseeability of the improvement in social aspect were the key features of this method. This method was used to scrutinize the social impact of workers in a crepe rubber factory in Sri Lanka. Results claimed that health and safety and social benefits/ social security of workers were severely affected jeopardizing working conditions and health and safety of the country or area. Findings further indicated that countermeasures proposed therein could better health and safety and social benefits/social security of workers by 62% and 18% respectively. Meanwhile, working conditions and health and safety of the country or area were also upgraded by 19% and 27% respectively.

Managers or factory owners (in case of RSS manufacture) may implement the nominated options as the next step (N.B. we are happy to mention that one of the crepe rubber factories has already initiated its improvement process after referring to our research). For the sake of continuous improvement in financial, environmental and social aspects, we recommend them to combine second or third method with the forth. Repetition may reveal new issue(s) at each iteration and mangers or factory owners may refer to our options when addressing those. At some point they may compare practical outcomes with the theoretical outcomes herein for confident implementations. Further, they can integrate new tools to our methods for optimizing their use; to us, this is the point on which future research should focus.

However, we strongly believe that our attempts would ultimately yield profits, increase in sales and lower toxic gases released into air. Moreover, uplifted factory reputation and working conditions are also perceivable. Though barriers still exist, the method and findings herein can immensely be beneficial in reaching the ultimate target of sustainability not only in rubber industry but also in other industries rooted in developing countries.

List of Publications

Full articles Published in Refereed Journals

Dunuwila, P., Rodrigo, V. H. L., & Goto, N. (2018). Financial and environmental sustainability in manufacturing of crepe rubber in terms of material flow analysis, material flow cost accounting and life cycle assessment. *Journal of Cleaner Production*, *182*, 587–599. http://doi.org/10.1016/J.JCLEPRO.2018.01.202

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http://doi.org/10.1016/J.RESCONREC.2018.01.029

Dunuwila, P., Rodrigo, V.H.L., & Goto, N. (2019). Assessing the financial and environmental sustainability in ribbed smoked sheet manufacture in Sri Lanka. *Indonesian Journal of Life Cycle Assessment and Sustainability.* (Accepted with minor revision)

Full articles to Be Published in Refereed Journals

Dunuwila, P., Rodrigo, V.H.L., & Goto, N. (2019). Improving financial and environmental sustainability in concentrated latex manufacture. *Resources, Conservation and Recycling.* (in preparation for submission)

Full articles Published in Refereed International Conference Proceedings

Dunuwila, P., Rodrigo, V.H.L., & Goto, N. (2017). Sustainability assessment in natural rubber industry: Case of a Sri Lankan crepe rubber factory. In *International Proceedings of International Rubber Conference 2017* (pp. 550–571). Jakarta, Indonesia. http://doi.org/10.22302/ppk.procirc2017.v1i1.460.

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