A multi-objective optimization tool for the Malawian tea industry with sustainability considerations

by
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Declaration

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Abstract

Corporate social responsibility (CSR) is fast becoming imperative for corporate governance in industry and business worldwide and is assuming an increasingly prominent role in the general discourse on globalization and sustainable development. The World Business Council for Sustainable Development has defined CSR "as the continuing commitment by business to behave ethically and contribute to economic development while improving the quality of life of the workforce and their families as well as of the local community and society". Different countries and organizations agree on the fundamental principles and spirit embedded in this definition. The major challenge, however, is that there are currently no standardised modalities by which it should be achieved nor a yardstick by which compliance can be graded. Differing perceptions of CSR have resulted in many disparate codes where they exist. In Africa, this problem is further exacerbated by a lack of awareness. In addition, there is an absence of a comprehensive management framework that would address, balance and integrate triple bottom-line considerations.

This dissertation primarily aims to address this gap. A tool to support this objective has been proposed, designed and tested in the field. The Malawian tea industry has been identified as a case study. A multitude of challenges in this industry includes child labour and deforestation as well as dwindling product quality and profit margins. These objectives have conflicting demands. The primary objective of this dissertation is to develop a multi-objective optimization tool to support decision-making processes in the Malawian tea industry. This work presents a novel decision support tool, called MOISAT (multi-objective optimization and integrated sustainability assessment tool), for the optimization of operating production processes while minimizing cost impacts and maximizing the long-term sustainability.

MOISAT is based on a combination of life cycle analysis (LCA), multi-criteria analysis (MCA), particularly, the analytic hierarchy process (AHP), and non-dominated sorting genetic algorithm (NSGA-II). LCA–based framework methodology is used to quantify the environmental, social and economic sustainability performance of tea production. AHP is applied to evaluate and rank different alternatives based on the judgment of decision makers. NSGA-II, an increasingly popular multi-objective optimization technique is employed to obtain a set of Pareto optimal solutions.

The developed tool is empirically tested on a case study of three tea companies in Malawi. Moreover, the applicability of the developed tool has been validated using usability testing, conducted through questionnaire survey and in-depth semi-structured interviews with eight decision makers as well as face to face discussions with experts. The results have demonstrated the usefulness of the tool in pinpointing environmental and social sustainability hot spots within the tea production life cycle stages that need further improvement. Furthermore, the results from this study have shown that the proposed algorithm is effective and has great potential to solve multi-objective optimization problems in the tea industry. Finally, the findings of this study will help decision makers in the tea industry to incorporate sustainability considerations into tea products, processes and activities.

Opsomming

Korporatiewe sosiale verantwoordelikheid (KSV) is vinnig besig om noodsaaklik vir korporatiewe bestuur in die industriële- en besigheidswêreld te word en neem ŉ toenemend prominente rol in die algemene diskoers oor globalisering en volhoubare ontwikkeling in. Die Wêreld Besigheidsraad vir Volhoubare Ontwikkeling het KSV gedefinieer as die voortgesette toewyding deur ŉ besigheid om eties op te tree en tot ekonomiese ontwikkeling by te dra, terwyl die lewensgehalte van die arbeidsmag, hul gesinne, die plaaslike gemeenskap asook die samelewing in die algemeen verbeter word. Verskillende lande en organisasies stem saam oor die grondbeginsels en goeie gees wat in hierdie definisie omsluit word. Die groot uitdaging is egter dat daar tans geen gestandaardiseerde modaliteite bestaan waardeur dit bereik kan word nie en ook geen maatstaf waarteen nakoming gegradeer kan word nie. Verskillende persepsies van KSV het tot gevolg gehad dat baie uiteenlopende kodes bestaan. In Afrika, is hierdie probleem verder vererger deur 'n gebrek aan bewustheid. Daarbenewens is daar is 'n gebrek aan 'n omvattende bestuursraamwerk wat drievoudige oorwegings aanspreek, balanseer en integreer.

Dit verhandeling is hoofsaaklik daarop gemik om aandag aan hierdie gaping te skenk. 'n Instrument om hierdie doelwit te ondersteun is voorgestel, ontwerp en in die praktyk getoets. Die Malawiese teebedryf is as gevallestudie geïdentifiseer. Menige uitdagings in die bedryf sluit kinderarbeid en ontbossing en kwynende gehalte van die produk en winsmarges in. Hierdie doelwitte het botsende eise. Die hoofdoel van hierdie verhandeling is om ŉ veeldoelige optimaliseringsinstrument om besluitnemingsprosesse te ondersteun in die Malawiese teebedryf te ontwikkel. Hierdie werk bied 'n nuwe besluitondersteuningsgereedskap, genaamd MOISAT (Multi-objective Optimization and Integrated Sustainability Assessment Tool), vir optimale werkproduksieprosesse, terwyl die minimalisering van koste-impak en die maksimering van die langtermyn-volhoubaarheid plaasvind. Die instrument is gebaseer op 'n kombinasie van lewensiklusontleding (LSO), multi-kriteria-analise (MKA), veral die analitiese hiërargiese proses (AHP), en veeldoelige optimeringsmetodes. LSO gebaseerde raamwerk metodes word gebruik om die omgewings-, maatskaplike en ekonomiese volhoubaarheidsprestasie van teeproduksie te kwantifiseer. AHP word toegepas om te evalueer en lys volgens rang verskillende alternatiewe gebaseer op die oordeel van besluitnemers. Nie-gedomineerde sorterings genetiese algoritme (NSGA-II), is 'n toenemende gewilde veeldoelige optimiseringstegniek en word gebruik om 'n stel van Pareto optimale oplossings te kry.

Die ontwikkelde instrument is empiries getoets op 'n gevallestudie van drie teemaatskappye in Malawi. Daarbenewens is die toepaslikheid van die ontwikkelde instrument goedgekeur met behulp van ŉ gebruikerstoets wat deur middel van vraelyste en diepgaande semi-gestruktureerde onderhoude met agt besluitnemers, asook gesprekke van aangesig tot aangesig met kundiges uitgevoer is. Die resultate het die nut van die instrument gedemonstreer deur die vasstelling van omgewings- en sosiale volhoubaarheidsbrandpunte binne die teeproduksielewensiklusstadiums wat verdere verbetering nodig het. Verder het die resultate van hierdie studie getoon dat die voorgestelde algoritme effektief is en 'n groot potensiaal vir die oplossing van 'n veeldoelige optimeringsprobleem in die tee-industrie inhou. Die bevindinge van hierdie studie sal besluitnemers in die tee-industrie help om volhoubaarheidsoorwegings te neem in tee produkte, prosesse en aktiwiteite.

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Dedication

To my parents Loti Taulo and Elida Mphepo

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List of Publications

Different parts of this work have already been published or are being published in international journals or conference proceedings. These publications are listed below:

Journal papers

1. Taulo, J.L., Sebitosi, A.B. (2016). Material and energy flow analysis of the Malawian tea industry. *Renewable and Sustainable Energy Reviews* 56, 1337-1350.
2. Taulo, J.L., Sebitosi, A.B., & Gondwe, K.J. (2015). Energy supply in Malawi: Options and issues. *Journal of Energy in Southern Africa* 26 (2), 19-32.
3. Taulo, J.L., Sebitosi, A.B., (2014). Proposing an integrated sustainability framework for the Malawian tea industry: a review (Manuscript)
4. Taulo, J.L., Groenwold, A., & Sebitosi, A.B. (2016). An integrated multi-objective optimization model for maximizing sustainability of the Malawian tea industry (Manuscript)
5. Taulo, J.L., Groenwold, A., & Sebitosi, A.B. (2016). Life cycle assessment applied to tea production: investigating environmental impacts to aid decision making for improvements in the Malawian tea industry (Manuscript)
6. Taulo, J.L., Groenwold, A., & Sebitosi, A.B. (2016). Exploring energy consumption and greenhouse gas emissions of tea manufacturing in Malawi (Manuscript)

Conference papers

1. Taulo, J.L., Sebitosi, A.B. (2015). Energy consumption analysis for the Malawian tea industry. *2015 International Conference on the Industrial and Commercial Use of Energy (ICUE)*, Cape Town, 18-19 August 2015, IEEE Conference Publications, ISBN: 978-0-6206-5913-0, ISSN:2166-059X, pp 191-198. (Peer reviewed).
2. Taulo, J.L., Sebitosi, A.B. (2013). Improving energy efficiency in Malawian tea industries using an integrated multi-objective optimization method combining IDA, DEA and evolutionary algorithms. *2013 Proceedings of the 10th Industrial and Commercial Use of Energy (ICUE)*, Cape Town, 20-21 August 2013, IEEE Conference Publications, pp 1-7. (Peer reviewed).
3. Taulo, J.L., Sebitosi, A.B., (2016). Application of material and energy flow analysis to the Malawian tea industry. *5th International Symposium on Energy Challenges & Mechanics-working on small scales*, 10-14 July 2016, Inverness, Scotland, UK. (Peer reviewed)

Nomenclature

$A.I_{i,w}$	Application rate of active ingredient *w* [kg/ha]
$AR_{N,f}$	Application rate of nutrient *f* [kg/ha]
$A_{i,f}$	Area applied with fertilizer nutrient type *f* [ha]
$A_{i,w}$	Area applied with pesticide type *w* [ha]
A_m^p	Emission of substance p per kg of made tea, if processing method m is chosen
A_t^{pr}	Emission of substance p per km and unit of green leaf r, if transport mode t is chosen
$CAP_i^{r,supp}$	Capacity of out grower i for green leaf r [kg]
CAP_m	Capacity of production method m [kg]
CAP_{sjt}	Required factory capacity using technology *s* at factory *j* during time interval *c*.
CAP_{sto}^0	Required factory capacity using technology *s* at factory *j* during time interval *c*.
$CAP_{ti}^{r,trans}$	Capacity of transportation mode t for green leaf r , on route from out grower i to the tea factory [ton-km]
$CEF_{f,op}^k$	Emissions factor per unit of energy [kg/MJ]
CR_i^r	Unit cost of raw material r bought from out grower i [US$/kg]
C_{ad}^f	Cost of job *a* when *d* workers are assigned [US$]
$C_{i,j}^f$	Unit cost of firewood [US$/m^3]
C_i	Weight of criterion *i* with respect to goal
C_{stm}	Unit cost of steam [US$/kWh]
$\dot{D}_{stm}$	Steam consumption rate [kg/h]
$EF_{N,f}$	Emission factor for fertilizer nutrient *f* [kg/kg N]
$EF_{g,w}$	Emission factor for pesticide type w [kg/kg]
$FC_{f,op}^u$	Average energy content of the fuel [MJ/kg]
F_k	Mass/flowrate of component k emitted in the environment [kg]
$GA_{v,i,t}^r$	Available amount of green leaf variety *v* from estate or tea field *i* at time period *t* [kg]

I_m^h	Number of injuries and illnesses in severity class h, if processing method m is chosen
N_{kj}^{temp}	Number of temporary agricultural jobs created (man-hours/ha)
P_i^D	Incident rate [ ]
$P_{ik,m}^B$	Working hours per kg of made tea under processing method m [h]
P_{ik}^B	Employee hours worked [h]
P_{kWh}^{el}	Unit cost of power [US$/kWh]
T_{jm}^{LC}	Working hours per kg of made tea under processing method m; [h]
T_{kj}^{perm}	Number of working hours per day [h]
T_{op}	Annual operating hours [h]
U_m^r	Amount of green leaf r consumed in technology *i* at factory *j* [kg]
W_{ij}	Flow of product obtained with technology *i* at factory *s* [kg]
W_j	Global weight of alternative *j*
$X_{a,d}^f$	Binary number (0 or 1)
$X_{i,j}^f$	Annual firewood consumption in tea factory *j*. [m^3]
X_{ij}^{RM}	Average distance from out grower i to the tea factory j [km]
X_{ijm}^{PL}	Binary variable (1, if processing method m is chosen, 0 otherwise)
$Xik_{v,i,k,m,t}$	Amount of green tea variety v shipped from estate or tea field to factory *j* with transport mode *m* in time period *t* [kg]
$\overline{Y_i^r}$	Upper limit of raw material availability [kg]
Y_i^r	Amount of green leaf r bought from out grower or estate i [kg]
$Y_{v,i,t}^r$	Total amount of green leaf variety *v* acquired from a tea field *i* at period *t*
Y_{xj}^k	Length of farming season for crop year [days/year]
Z_{jk}^p	Quantity of product p produced in factory j units (equals demand of product) [tons]
d_{ji}^p	Number of permanent agricultural workers required per hectare of tea grown *j*
x_{ij}	Local weight of alternative *j* with respect to *i*
$x\gamma_{k,i}$	Characterization factor for burden k

α_{jk}^{f}	Dimensionless matrix that matches tea types to correct processing technologies
α_{jm}^{LC}	Labour cost per hour [US$/hr]
α_{kj}^{NC}	Number of labour in j^{th} category
βY_{ik}^{D}	Number of injuries and illnesses
$\beta_{f,op}^{p}$	Quantity of fossil fuel (diesel) for producing one hectare of green leaf [*l*]
β_{f}^{u}	Yield of made tea produced from tea variety *j* [kg/ha]
β_{kj}^{LC}	Wages and benefits per category of the i^{th} labour [US$]
β_{t}^{p}	Labour requirements for processing stage
γ_{lpt}^{FP}	Market price of product p sold at market l in the time period t [US$/kg]
λ_{max}	Maximum eigenvalue
μ_{ic}	Material balance coefficient for technology i and raw material r
φ_{jm}^{PL}	Utility cost per kg of made tea, if processing method m is chosen [US$/kg]
ψ_{jk}^{PL}	Unit transport costs of green leaf delivered from out grower or estate *i* to factory *j* [US$/ ton-km]
ψ_{k}^{f}	Fraction of land occupied by tea variety
ω_{j}	Weighting factors for each environmental impact category j
DP_{m}	Units of product depreciation, if processing method m is chosen [US$]
TC_{ti}^{r}	Cost of transportation per kilometre of one unit of green leaf, with transport mode t from out grower i [US$/km]
TY_{ti}^{r}	Amount of green leaf r, delivered from out grower or estate i, using transport mode t [kg]

Greek Characters

Ω	Feasible region
ε	Epsilon constraint
ω	Priority vector or weight
ψ	Overall environmental impact [kg]

Operators

$\forall_i$	For all
$\nexists$	There does not exist
$\preccurlyeq$	Precedes or equal to
$\exists_j$	There exist
$\in$	Element of
$\wedge$	Logical And

Subscripts and Superscripts

i	suppliers or estates $(i = 1, \ldots, I)$
r	raw materials $(r = 1, \ldots, R)$
m	tea processing method $(m = 1, \ldots, M)$
t	transportation mode $(t = 1, \ldots, T)$
p	substance $(p = 1, \ldots, P)$
h	injury severity class $(h = 1, \ldots, H)$
j	tea factories $(j = 1, \ldots, J)$
k	final product or tea grades $(k = 1, \ldots, K)$
w	warehouses $(w = 1, \ldots, W)$
d	number of workers $(d = 1, \ldots, D)$
a	jobs $(a = 1, \ldots, A)$
b	categories of labour $(b = 1, \ldots, B)$
q	tea factory machines $(q = 1, \ldots, Q)$
v	tea varieties grown $(v = 1, \ldots, V)$
e	energy sources for crop cultivation (e = 1,…, E)

Acronyms

ADP	Abiotic Depletion Potential
AHP	Analytic Hierarchy Process
AIT	Asian Institute Of Technology
AP	Acidification Potential
BCR	Benefit Cost Ratio

BOD	Biological Oxygen Demand
CED	Cumulative Energy Demand
CEPCI	Chemical Engineering Plant Cost Index
COD	Chemical Oxygen Demand
CSR	Corporate Social Responsibility
CTC	Cut-Tear-Curl
DCFROR	Discounted Cash Flow Rate Of Return
ELCA	Environmental Life Cycle Assessment
EMOA	Evolutionary Multi-Objective Optimization Algorithm
EP	Eutrophication Potential
ETP	Ethical Tea Partnership
FAETP	Freshwater Aquatic Ecotoxicity Potential
FAO	Food And Agriculture Organization
FAOSTAT	Food And Agriculture Organization Statistics
GA	Genetic Algorithm
GDP	Gross Domestic Product
GWP	Global Warming Potential
HTP	Human Toxicity Potential
ILO	International Labour Organization
IRR	Internal Rate Of Return
LCSA	Life Cycle Social Assessment
LTP	Lawrie Tea Processor
MAETP	Marine Aquatic Ecotoxicity Potential
MCA	Multi-Criteria Analysis
MOGA	Multi-Objective Genetic Algorithm
MOISAT	Multi-objective Optimization and Integrated Sustainability Assessment Tool
MVA	Manufacturing Value Added
MWK	Malawi Kwacha
NPGA	Niched Pareto Genetic Algorithm
NPV	Net Present Value
NSGA-II	Non-Dominated Sorting Genetic Algorithm-II

NSO	National Statistical Office
ODP	Ozone Depletion Potential
PAES	Pareto Archived Evolutionary Strategy
POCP	Photo Oxidant Creation Potential
RWS	Roulette Wheel Selection
SETAC	Society Of Environmental Toxicology And Chemistry
SLCA	Social Life Cycle Assessment
SPEA	Strength Pareto Evolutionary Algorithm
TAC	Total Annualized Cost
TAML	Tea Association of Malawi Limited
TETP	Terrestrial Ecotoxicity Potential
TF	Theaflavins
TMR	Transparency Market Research
TR	Thearubigins
TRFCA	Tea Research Foundation Central Africa
UNDP	United Nations Development Programme
UNEP	United Nations Environmental Programme
VEGA	Vector Evaluated Genetic Algorithm

Chapter-1
Background and Motivation

1.1 Introduction

This dissertation focuses on multi-objective optimization of the Malawian tea industry with sustainability considerations. The genesis of this study is the clear need for an industry-wide framework and tool for measurement, evaluation, and optimization of sustainable performance in the tea industry. The purpose of the research work presented in this doctoral dissertation is to develop a multi-objective optimization tool to support decision-making processes in the Malawian tea industry. This introductory chapter aims to set the foundation on which this thesis is built. It provides a background of the study and motivates the significance of the work reported in this thesis. The chapter also describes the research problem addressed and the aims and objectives of the study. Furthermore, it presents the scope and limitations of the study and the main contributions of this work. The chapter concludes by describing the approach and methods used to undertake this research, together with an overview of the thesis structure.

1.2 Background and Context

Managing environmental, social, and financial performance simultaneously has increasingly become an imperative for today's corporate businesses. However, there are many obstacles associated with integrating social, environmental and financial aspects in day-to-day decision-making that have yet to be addressed. The global manufacturing industry faces constant scrutiny about its sustainability impacts. In particular, the tea industry, which consumes large amounts of energy and natural resources thus producing considerable environmental and social impacts, needs to systematically identify, measure and evaluate its sustainability performance (Koskela, 2011). Fierce competition in today's global markets and strict environmental regulations also urge business enterprises to integrate sustainability into their operations (Zhou et al, 2012). Moreover, environmental and social pressure push business enterprises to demonstrate their contribution towards sustainable development as well as reporting their overall sustainability performance (Labuschagne et al, 2005). This, together with rising production costs, collapsing demand and volatile commodity prices, besides increasing globalization, are causing dynamic forces of change requiring corporate businesses to be more adaptive to change (Krantz, 2010), hence striving for higher operational efficiency and gaining a competitive advantage.

The Malawian tea industry is undoubtedly the biggest provider of employment in the country and a third major earner of foreign exchange for the economy (NSO, 2011). However, this century old industry is now facing a multitude of social, financial and environmental challenges that threaten its survival. The tea industry is facing survival threats such as high cost of production related to rising labour costs and primary materials, coupled with collapsing demand and volatile prices on a global scale, as well as increasing and fierce competition from major tea producers (Lalitha *et al.*, 2013; Onduru *et al.*, 2012; Wal, 2008). At the same time, the spiralling cost of inputs (electricity, fuel, pesticides and chemical fertilizers) experienced by the industry is seriously eroding its competitiveness on the global market. Moreover, the numerous taxes and levies tea companies have to bear is also putting considerable strain on the already fragile production cost and impeding tea industry's competitiveness.

Moreover, the environmental and social performance of tea production is of growing concern. Consumers are increasingly interested in the environmental impacts of tea production and processing. Investors want to judge how much reasonable governance should be made for environmental compliance. Tea manufacturing is also facing legal and public pressure to incorporate environmental goals into its corporate strategy. Tea companies are being pressurised to publicize their actions and contribute to the heightened awareness of environmental issues among all businesses. More recently, importers were also showing concern about unethically produced tea as they demanded strict compliance with employee social and welfare standards by tea companies (Blowfield, 2003; ETP, 2012). Furthermore, government and communities are gradually emphasizing corporate social responsibility. Consequently, there is a need for integrating the economic, social and environmental concerns in its operations, strategies and decision-making processes, and to optimize balance amongst these three dimensions of sustainability (Szekely & Knirsh, 2005).

Although several sustainability optimization models have been developed over recent years, a systematic framework as well as holistic tool to track, measure, quantitatively evaluate and optimize sustainable performance is lacking. In addition, no sustainability optimization model integrating economic, environmental, and social aspects of tea production exists. Furthermore, there are still many research gaps in the literature that need to be filled. Intense research is needed to create a clearer understanding of the measurement of social sustainability and how it can be integrated into sustainability assessment models as well as contemporary decision-making. Motivated by these costs, environmental and social concerns, this study proposes a novel multi-objective framework that simultaneously takes the economic, social and environmental aspects of tea production into account.

The primary purpose of this research is to develop a multi-objective optimization tool to support decision-making processes in the Malawian tea industry. This is to enable creation of a tool for the measurement, evaluation and subsequent improvement of sustainable performance in this industry. This dissertation provides a framework and tool that can enhance sustainable performance improvements in the tea industry in Malawi. The framework combines life cycle assessment (LCA); multi-criteria analysis (MCA), specifically the analytic hierarchy process (AHP);

and sustainability performance indicators (SPIs) methods to provide a single performance index of sustainability. An evolutionary multi-objective non-dominated sorting genetic algorithm (NSGA-II) is used to simultaneously optimize the tea production system on a number of economic, social, and environmental objectives. Finally, the proposed tool is unique in its ability to provide decision makers in the tea industry with a multi-objective model to determine the trade-offs among economic, social and environmental considerations.

1.3 Research problem

The main research problem addressed by this study is the development of a multi-objective optimization tool to support decision-making processes in the Malawian tea industry. Decision-making in tea production and processing has become more complex and involves multiple objectives – often conflicting in nature. The tea industry globally strives to maximize its profitability while reducing costs by operating more efficiently, or minimize the environmental impacts and maximize the well-being of stakeholders. Solving these complex decision problems requires the use of mathematical techniques that are formulated to take simultaneous consideration of conflicting objectives. Multi-objective optimization has been well-recognized as a useful technique for the simultaneous optimization of several competing objectives while finding an optimum solution over a feasible set of decisions (Marler & Arora, 2009). They offer a choice between trade-off solutions, providing decision makers with sufficient options necessary to optimize the balance among all three dimensions of sustainable performance (Chaabane *et al.*, 2010; Ramudhin *et al.*, 2012).

Considerable research has been done to explore the use of multi-objective optimization to solve decision problems in the industry. As a result, various models have been developed to solve these multi-objective optimization problems. However, despite of the development of several optimization models over recent years, a systematic framework, as well as a holistic tool to track, measure, quantitatively evaluate and optimize sustainable performance in the tea industry, are lacking. More importantly, no published literature work exists that integrates and optimizes a balance between the three elements of sustainable performance in developing countries, including Malawi. The objective of this study is to fill this gap. This study proposes a novel multi-objective framework that simultaneously considers the economic, social and environmental aspects of tea production in Malawi. Major novelties of this work include (1) first multi-objective optimization model for sustainable tea production; (2) consideration of the three-dimensional sustainability, simultaneously optimizing the economic, social, and environmental impacts; and (3) integration of environmental and social concerns that follow life cycle procedure in a multi-objective framework.

1.4 Motivation for study

Several emerging issues facing the Malawian tea industry motivate this study. While the role of sustainability is of utmost importance, considerably less knowledge exists on how to systematically measure, evaluate and optimize the sustainability performance of the tea industry. The research interest emerged from concerns raised in recent years regarding the sustainability of the Malawian tea production system. The tea industry faces increasing environmental, social and economic challenges, which entail complex decision-making processes. To secure its continued social license to operate, the industry must respond to those challenges by engaging with many different stakeholders and addressing their sustainability concerns. In addition, to achieve the goal of sustainability, it is important for tea industry decision makers to have an understanding of the environmental, economic and social impacts of their activities and processes. The industry must also be able to measure and assess its sustainable performance and make continuous long term improvements. More importantly, the tea industry has recognized that sustainability issues define part of the new business reality, in which the traditional business response no longer fully satisfies the expectations of investors, communities, employees and other stakeholders. Now tea companies must at least implement sustainability programmes to appease stakeholders and keep pace with peers in the industry.

The study is also motivated by the fact that not much in the literature offers a holistic approach to sustainability. Existing efforts have treated each of the three pillars of sustainability separately, based on the field of interest groups (for example, environmentalists, sociologists, economists, etc.). In addition, the social dimension of sustainability has not been given the prominence it deserves; and surprisingly, discussion of this element has received relatively less attention in the sustainable production. Thus, there is a need for a systematic tool to simultaneously measure and evaluate sustainability at factory or organizational level. Moreover, there is a particular need to develop tea industry-specific indicators with a view to present a balanced and holistic approach to plant-level sustainability performance, encompassing information on all different dimensions.

Further motivation is provided by the fact that extensive research has been undertaken in the tea industry over the past three decades. However, most existing research work to date has focused mainly in the areas of agronomy, physiology and plant breeding. Surprisingly, no study exists which investigates the sustainability aspects of tea production. Consequently, there is a need for development of tools and methods that will enable tea companies in Malawi to evaluate sustainability metrics of their operations. Such information is necessary for the industry to support quantification, follow-up, management, improvement and communication of environmental work to various stakeholders. Finally, the main motivation of this work is to decrease the cost of production of manufactured tea, as well as contribute towards environmental protection and well-being of tea workers and communities around tea plantations in the country.

This study identified the Malawian tea industry as a suitable research context due to its significant contribution to the world tea production and the country's gross domestic product (GDP) and employment. The industry also presents one of the most labour and energy intensive sectors of the manufacturing industry. It is therefore of particular interest in the context of both local and global environmental discussions, as well as the industry's sustainability commitment and reputation for ethical business and manufacturing practices.

1.5 Purpose of the study

The main hypothesis proposed in this work is that no proper management tools exist to assist in decision-making processes in the cultivation, production and manufacturing of tea. Thus, the primary purpose of this research is to develop a multi-objective optimization tool to support decision-making processes in the Malawian tea industry. The study aims at creating a tool for the measurement, evaluation and subsequent improvement of sustainable performance of the tea industry. The tool comprises three main sub-models, namely the economic, environmental, and social model. Its role is to provide quantitative evaluation on the sustainability of the tea industry. Furthermore, the model integrates sustainable performance indicators, the essential components of life cycle assessment (LCA), multi-criteria decision analysis (MCA), specifically the analytical hierarchy process (AHP) and the non-dominated sorting genetic algorithm (NSGA-II). The model is integrated in the life cycle assessment framework, while an index is then proposed to describe the sustainability of the tea industry in terms of cradle-to-gate life cycle stages. The model is tested and validated by case studies of typical tea factories in Malawi.

In order to achieve the research aim, this dissertation pursues the following objectives:

(1) To empirically investigate the current practices of the Malawian tea industry;
(2) To identify and understand critical factors that influence productivity and sustainability of tea processing companies;
(3) To explore and describe the existing literature on theory and practical interventions (globally) in pursuit of environmental, economic, and social performance related to tea production;
(4) To develop an integrated optimization model that maximizes the economic and social value of the tea production system in Malawi, while minimizing its most significant environmental impacts; and
(5) To evaluate the performance, usability and reliability of the created tool by case studies.

1.6 Research questions

The overarching research question that guides this study is:

How can decision makers in the tea industry be empowered to achieve sound financial performance within environmentally sustainable and socially responsive bounds?

In order to provide clarity to the broad question, six sub-questions were developed:

RQ1: What are the situation and status of sustainability practices and performance in the Malawian tea industry?

RQ2: What are the critical productivity and sustainability factors that need to be considered for the sustainability of the Malawian tea industry?

RQ3: How can the sustainable performance of the tea industry be measured?

RQ4: What are the environmental, economic and social impacts related to tea production in Malawi?

RQ5: How can the sustainable performance of the tea industry be optimized?

RQ6: Can the developed tool be implemented on a large scale in the tea industry? What barriers exist with regard to the successful implementation of MOISAT in the tea industry?

1.7 Scope of the study

The scope of this study is the Malawian tea industry, and covers its agricultural and manufacturing activities. The operations of the tea industry are divided into two subsystems: the farm and factory. The main activities on the farm include cultivation, fertilization, pest and disease control (spraying), plucking (harvesting) and crop transportation. The main activities at the factory include withering, rolling, fermentation (oxidation), drying, sorting and packing. In order to ensure the manageability of the system (i.e. not too large and complex to describe and evaluate), the life cycle social assessment (LCSA) is simplified by drawing an ad hoc system boundary that excludes all but a few upstream and downstream processes. Therefore, this study has a cradle-to-gate system boundary and starts at the farm gate where freshly harvested green leaves are collected and ends at the production of dried tea at the factory gate. Upstream activities such as nursery establishment, production of farm inputs (seeds, fertilizers, pesticides, machinery) as well as downstream activities (e.g. distribution and use stage) have been excluded from the assessment. In addition, impacts on and considerations of the consuming nations have not been investigated. Furthermore, the research does not cover tea industries outside Malawi.

1.8 Research methodology

The research design for this study is an explorative mixed method, as little is known about the phenomena under study. Combining qualitative and quantitative research approaches help overcome some of the limitations of singular data collections (Creswell, 2013). The study incorporates the collection of both primary and secondary data for an in-depth investigation. Secondary data has been gathered through publications and reports of the Tea Association of Malawi (TAML), Tea Research Foundation Central Africa (TRFCA), Limbe Auction Floors, and National Statistical Office, database of the Food and Agriculture Organization Statistics

(FAOSTAT), and individual tea companies. Other information related to the industry has been collected from unpublished works like doctoral theses, research reports, books, periodicals, journal articles, and various other documents of tea companies. The present study is made for a period of seven full years of operations in order to reveal seasonal and other dynamic changes in the business environment of the industry.

The research begins with a literature review on productivity, sustainability and multi-objective optimization. The gaps in productivity and sustainability assessment are identified, followed by research aims and objectives. A comprehensive literature review is conducted to discuss multi-objective optimization, sustainability as well as life cycle assessment. To get the primary data for the sustainable tea production in Malawi and for the model development, an industrial survey, including a questionnaire survey, a semi-structured interview and direct on-site measurements is conducted. The questionnaires are used to collect information from eight tea factories in Malawi. Purposive and convenience techniques are applied to select a sample of factories for this study. All the information collected from the questionnaire, like raw materials, energy consumption, waste and emissions, the key indicators for the model will be used as the foundation in the data analysis. In order to have in-depth discussions and more open ideas in relation to some issues generated in the questionnaire survey, interviews were conducted following the questionnaire. The model development is based on the results of questionnaire survey, semi-structured interviews and a review of relevant literature. Validation of the developed model is done through model implementation following the case study method as described by Yin (1984); Zainal (2007). Details of the research methodology adopted in this study are provided in Chapter 5.

The research presented in this dissertation is divided into three phases. Phase 1 comprises a survey of tea manufacturing operations of selected tea factories. This entails an operational audit, measurement and analysis of actual process parameters; inventory and cost of inputs, namely materials, machine hours and human hours, as well as outputs, which are the products and by-products. Both qualitative and quantitative interviews are conducted to examine and understand the factors affecting the sustainable performance of the industry. Phase 2 of the study concentrates on problem formulation, definition of constraints, model development, testing and validation. The LCA methodology combined with MCA, particularly the AHP is applied to evaluate the environmental and social performance of the Malawian tea industry. Phase 3 of the study covers the application, demonstration and evaluation of the model in selected tea companies.

1.9 Significance of the research

The study has considerable practical significance as it would establish the status of sustainability practices in the Malawian tea industry and identify factors critical to sustainable productivity, which would provide a model for other industries facing similar challenges. In addition, the study contributes to a variety of interrelated economic, social and environmental objectives for sustainable development in the tea industry including: (i) the promotion of economic growth and encouragement of an open economy; (ii) creation of productive employment, improvement of standards, increased access to education and health care, and (iii) protection of the natural environment as well as improvement of environmental performance. Further, the research will support decision makers in the Malawian tea industry to understand the compromises between economic objectives and environmental as well as social concerns related to tea production. The study will increase awareness of environmental and social responsibilities and implement practices that contribute to a sustainable future of the tea industry. The study also provides evidence on how the Malawian tea industry can use multi-objective optimization techniques to respond to the organizational pressures for sustainability with the aim of gaining legitimacy, and enhancing operational efficiency.

1.10 Contributions

The study expects to contribute in a number of ways to the existing literature in the field of sustainable production. The major areas of contributions are:

- An integrated multi-objective optimization model for sustainable tea production: the main contribution of this study is the development of an integrated multi-objective optimization model and its applicability in the tea industry. To the best of the researcher's knowledge, there is no such tool that incorporates all three dimensions of sustainable performance in a single overarching framework for the tea industry.
- A framework that enables consideration of the three-dimensional sustainability, simultaneously optimizing the economic, social, and environmental impacts following life cycle analysis procedure in a multi-objective framework.
- A unique NSGA-based algorithm that integrates sustainable performance indicators (SPI), LCA, MCA, particularly the AHP and an evolutionary multi-objective optimization algorithm (EMOA).
- New knowledge and understanding of productivity and sustainable development: the results from the research will contribute to an improved understanding of the link between productivity and sustainable development and show that improvement of total factor productivity could be the main road to sustainable development. The study will help management in tea companies to develop productivity management systems that ensure that sustainability issues are taken into consideration in business performance improvement decisions.
- Description of the situation and challenges of the tea industry: the present study will report on the current situation concerning sustainable production and challenges confronting its realization in the Malawian tea industry. The overview of the current situation and challenges are undoubtedly beneficial for both industry and academia as it enable identifying actions required for the improvement of sustainability performance. Hence, it provides the basis and support for realizing sustainability in the tea industry.

- The study is expected to contribute to scientific knowledge on the conceptual framework on sustainable development. The research also contributes to the literature by providing a process whereby managers can measure sustainable performance and use this information to inform decision-making. The proposed study therefore stands to provide significant policy recommendations that will contribute to the attainment of the goal of sustainable development.

1.11 Limitations of the study

The limitations of the study can be categorized in limitations along the scope of the research, sample size, research methods, and time constraints. Creswell (2005) defines limitations as the problems underlying any research design. Specific limitations may include errors in site-level data collection and measurement as well as weakness in the measurement instrument. Identification of such limitations is productive because, as Mc Millan and Schumacher (2006) assert, the validity of inferences based upon the outcomes of quantitative research is increased through acknowledgement of the limitations of the study.

Several limitations to this study influence its validity and authenticity. Firstly, the sample size used in this study was relatively small as it included eight out of twenty-one tea factories in Malawi. The inclusion of more factories in the design would have made the results more generalizable. Further, the study is limited by the lack of data from those tea companies that did not participate in this study. Including non-participants in future studies would greatly enhance the understanding of the Malawian tea industry. Secondly, the study is limited by potential selection bias. Tea companies were selected for the study based on their willingness to participate. No information is presented concerning those companies that declined to participate in the study, which could limit the generalizability of these findings. Thirdly, the major limitation of this study concerns the disclosure of sensitive information such as wages, salary structure, and revenues generated by the enterprises. All of the tea companies were only willing to share a limited amount of data because of confidentiality. Fourthly, there are also methodological limitations arising from the focus of this study: the main one being that the validity of the results depends on the sincere reporting of the key informants interviewed and their ability to recall past events accurately and precisely. Furthermore, the data used in this study represents only seven years, a period that is not a representative of all data by any means. An extension of this analysis to include more years would provide a more robust set of results. Details of the limitations of this study are provided in Chapter 9.

1.12 Structure of the thesis

The dissertation comprises nine chapters and these chapters are organized as follows:

Chapter 1 introduces the research background, formulates the problem, describes its significance, and presents a brief outline of the research methodology used to collect data for the study. The chapter concludes by providing the organization of the study as well as noting some limitations and contributions.

Chapter 2 provides a discussion of the existing situation of the Malawian tea industry. It sheds light on the Malawian tea industry by highlighting the major trends and shifts in relation to the sustainability concept, reveals how the tea industry can cope with market shifts, and challenges with the help of multi-objective optimization modelling.

Chapter 3 reviews the available literature on the key concept of sustainability, drivers for and benefits of sustainable production as well as frameworks, tools and methods for evaluation of sustainability. It also presents an overview of the productivity concept; approaches to productivity measurement as well as its linkages with environmental and social sustainability.

Chapter 4 reviews the literature on multi-objective optimization, the central topic of this dissertation. It presents the background as well as the basic concepts of multi-objective optimization. In addition, the chapter introduces the principles of dominance and Pareto optimality, briefly describes the different methods, including classical and evolutionary algorithms for solving multi-objective optimization problems. This chapter also contains a brief discussion of the basic concepts, features and working flow of genetic algorithms. Furthermore, a brief description of the state-of-the-art multi-objective evolutionary algorithms, specifically the NSGA-II is provided.

Chapter 5 provides a discussion about the research methodology adopted for this study. It also considers the philosophical assumptions underpinning it, research design and strategy as well as the method of data collection and analysis. The pragmatic research paradigm is adopted, which allows both the qualitative and quantitative data collection methods to be used. The chapter concludes with a discussion of the strategies that were used to ensure that the results of this study are valid, reliable and trustworthy.

Chapter 6 presents the analysis of data, findings and discussion of addressing research objectives 1 and 2, which determines the current levels of sustainability and productivity in the tea industry, and identifies the critical factors negatively affecting the productivity of tea manufacturing in general and Malawi's tea industry in particular. The chapter also provides a discussion about the selection and identification of the most important indicators for the sustainability of the tea industry. A framework to assess the sustainability performance of the Malawian tea industry and to calculate the overall composite sustainability index is also discussed.

Chapter 7 introduces the MOISAT-NSGAII tool. The proposed tool, which is named Multi-objective Optimization and Integrated Sustainability Assessment Tool (MOISAT), is based on the literature review and industry survey. The chapter also discusses the process for generating indicators, followed by a detailed assessment of the indicators. Both qualitative and quantitative methods are used for indicators' evaluation. The AHP method is applied in this study to evaluate the importance of the indicators against each other.

Chapter 8 focuses on the empirical testing of the MOISAT model. A case study is conducted based on the developed model. It is used to highlight its capabilities as well as demonstrate its applicability as a tool to evaluate the sustainability performance of the tea industry. Following the validation of the model, the results of the empirical study are presented.

Chapter 9 presents the conclusions and summarizes the major findings along with the main contributions of this research. It also highlights the major limitations of this study and suggests directions for further research work.

1.13 Chapter summary

This chapter has attempted to provide an overview of the research conducted. It started with the background of this study. The research problem was identified, followed by defining the research objective and scope. It also discussed the significance of this research and the necessity of conducting it. This thesis comprises nine chapters that present comprehensive aspects of this research undertaken. The structure of the thesis was also presented here. The next chapter provides a background of the Malawian tea industry. It presents a brief history of Malawian tea industry and provides an industrial analysis to understand the dynamics in the national industry compared to the global industry. Furthermore, it sheds light on this industry by highlighting the major trends and shifts in relation to the sustainability concept, reveals how it can cope with market shifts, and challenges with the help of multi-objective optimization modelling. Finally, it explores the current literature to identify existing challenges faced by this industry.

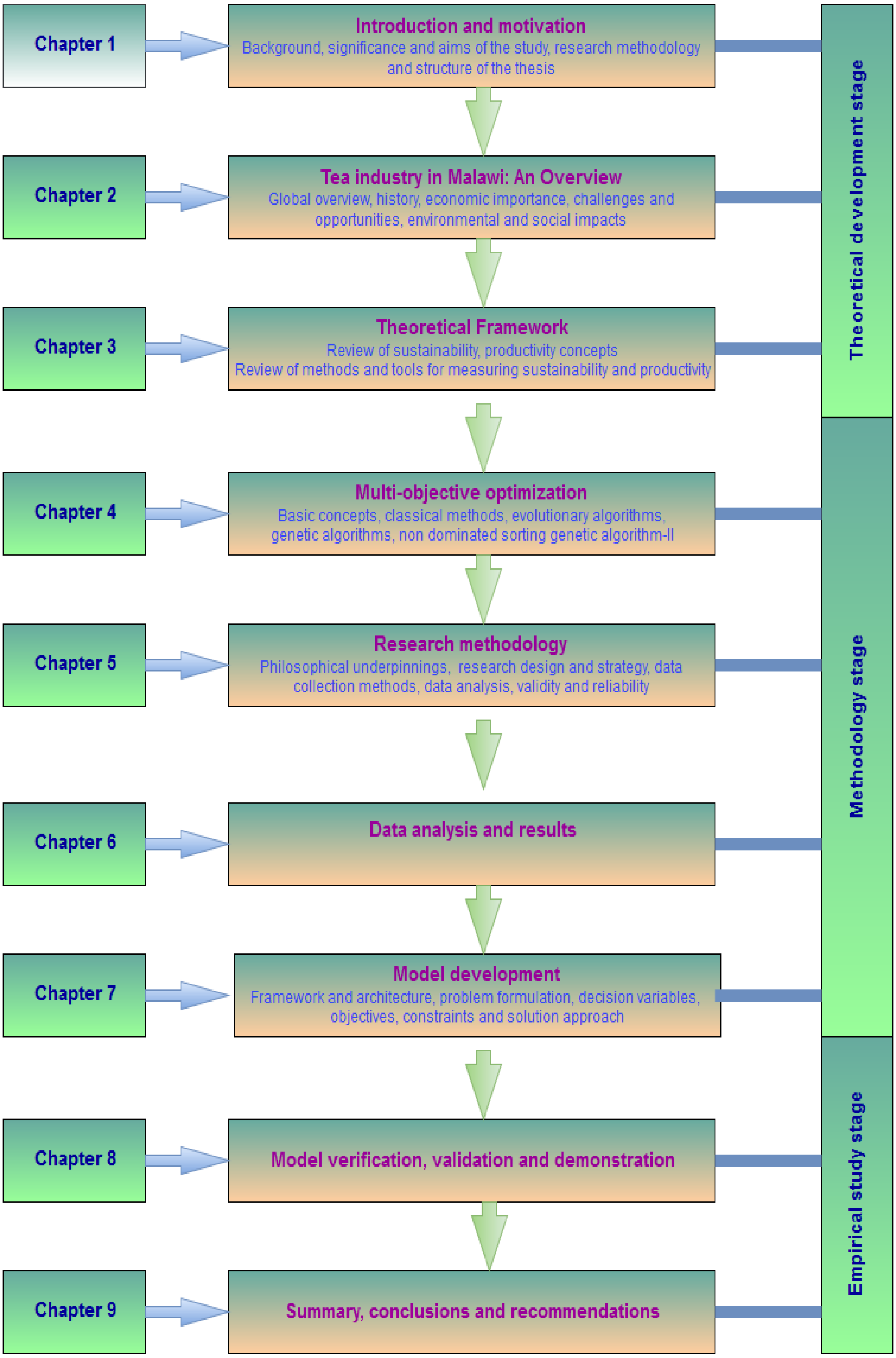

Figure 1.1: Structure of the research

Chapter-2
Tea industry in Malawi: An overview

2.1 Introduction

The previous chapter introduced this research, specified the purpose of the study and the underlying research problem, established the overarching research question, highlighted the significance of the research and justifications for selecting the Malawian tea industry, and presented the structure of the dissertation. The aim of this chapter is to present the background information about the Malawian tea industry. The chapter is divided into six main sections. The second section focuses on the global situation of the tea industry in terms of production, consumption and exports. The third section discusses tea as a beverage, its geographical origin and history. The health benefits of tea drinking are also presented in this section. The fourth section provides an overview of the Malawian tea industry, which shows its brief history, economic and social importance, and structure, including its current situation in terms of production, harvested area, and productivity. The fifth section describes some of the major challenges facing the industry in the global environment. The sixth section presents the environmental and social impacts associated with tea cultivation and processing. The chapter closes with the summary of the key findings from this part of the study.

2.2 The global tea industry

Tea has become an increasingly important global commodity in the world market and one of the main sources of foreign exchange for developing countries like Malawi. Today, it is a US$40.7 billion industry in terms of global retail value, and employs several million people worldwide (Friend, 2013). The global tea market is predicted to reach US$47.20 billion by 2020, growing at a compound annual growth rate of 2.8% from 2014 (TMR, 2015). Moreover, tea production occupies about 4 million hectares of land worldwide in more than 52 countries. There has also been a significant increase in world tea production and exports over the last five decades. World tea production has risen from 983.8 million kilograms in 1961 to 5063.9 million kilograms in 2013 (FAO, 2015b). At the same time, world tea exports are estimated to have increased from 592 million kilograms in 1961 to 1768.5 million kilograms in 2013 (Figure 2.1).

Figure 2.2 depicts the world's major tea producing countries. At present, China is the world's largest tea producer, contributing 38% of global tea production, followed by India (24%), Kenya (9%), Sri Lanka (7%), and Turkey (5%). Tea is primarily produced in Asia and Africa, with China, India, Kenya, Sri Lanka, and Turkey accounting for approximately 82% of world production and around 73% of global tea exports. Major tea growing countries in Africa are Kenya (67%), Uganda (9%), Malawi (7%), Tanzania (6%), Rwanda (4%), Mozambique (4%) and Zimbabwe (3%). Apart from these countries, tea is also produced in many more regions including South America (Argentina and Brazil), the Near East (Iran and

Turkey), the Commonwealth of Independent States (Russia), and Georgia. The world's five largest consuming nations are China, India, Turkey, Russia, and the United States of America. Together, these countries consume 65% of the world tea production. The subsequent four largest consumers are Pakistan, Japan, the United Kingdom, and Egypt.

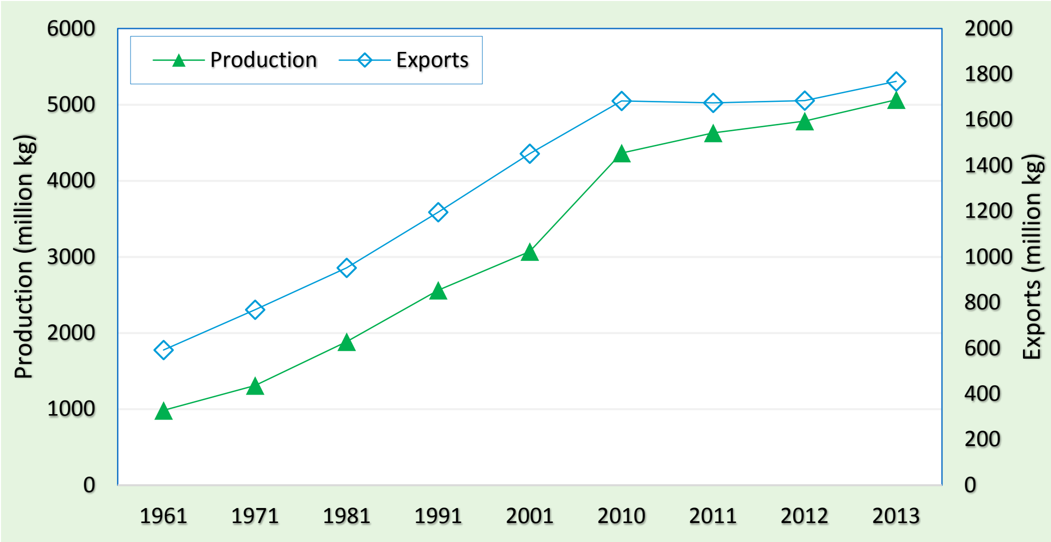

Figure 2.1: World tea production and exports 1961–2013. *Source: FAO (2015)*

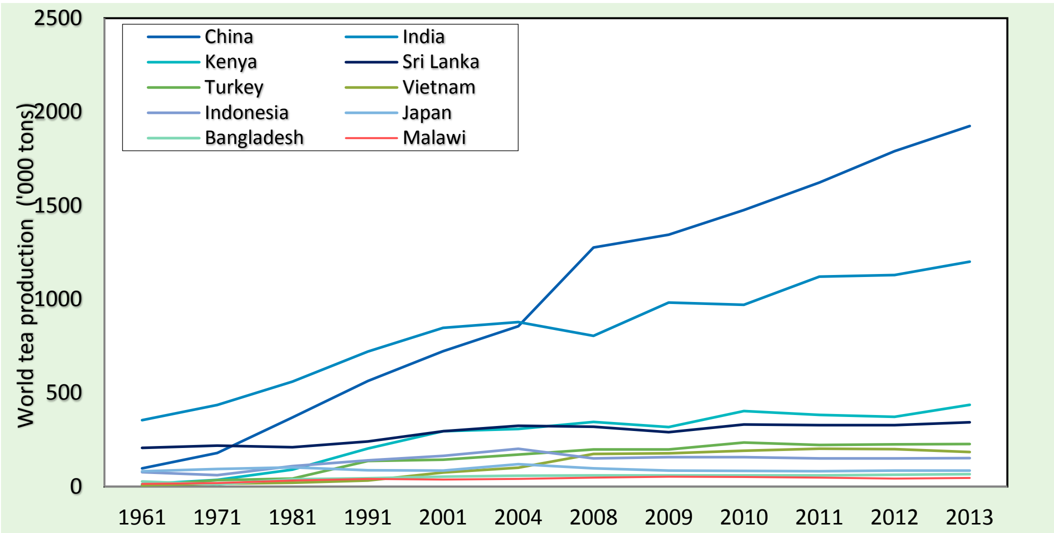

Figure 2.2: Selected world tea production statistics for the years 1961–2013. *Source: FAO (2015)*

2.3 Tea in perspective

This section provides an in-depth understanding of tea, its origin and history, production processes, and health benefits.

2.3.1 Botanical and agricultural aspects

Tea is undeniably the world's oldest and most widely consumed beverage, second only to water (Gramza-Michalowska, 2014). Recent statistics have shown that more than two-thirds of the world's population drink tea, with about 4.5 billion kilograms of tea consumed annually (Khan & Mukhtar, 2013). Tea is made by infusing hot water with the dried and processed leaves of the plant *Camellia sinensis* (Cabrera *et al.*, 2003). The tea plant is a perennial, evergreen shrub of the *Theaceae family*, currently grown on approximately 4 million hectares worldwide (FAO, 2015b).

Tea is grown under a wide range of agro-economic conditions extending from the tropics to the subtropics. The plant flourishes best in a warm and humid climate with plenty of rainfall evenly distributed throughout the season, high altitudes as well as weak acidic and well-drained soils. More precisely, tea grows particularly well in areas with wide temperature ranges (10–30°C) throughout its growing season. It also requires high humidity (rainfall ranging from 1250 to 2500 mm annually); well-drained fertile acidic soils (acidic pH in the range 4.5 to 5.5); sloping ground (0.5–10 degree slopes); and a fairly high altitude (up to 2000 m) (FAO, 2015b; Owuor, 2011). These meteorological conditions are known to affect not only tea yield and the normal growth and development of tea, but also tea quality. Earlier reviews of the environmental requirements of tea include (Carr, 1972), (Carr & Stephens, 1992), and (Shoubo, 1989).

Tea has gained increasing popularity due to its astringent taste, briskness, and flavour (Muthumani & Kumar, 2007). In addition, the combination of its relatively low cost and wide availability, coupled with its stimulating effects have strongly contributed to the growth in tea consumption worldwide. More recently, the multiple health promoting effects of tea have also attracted considerable interest in academia, and these have been widely reviewed in a series of papers (Balentine *et al.*, 1997; Blot & McLaughlin, 1997; Hollman *et al.*, 1997; Wiseman *et al.*, 1997).

Many different kinds of tea are consumed, the three major types being black, green, and oolong; which are essentially derived from the leaves of the plant, *Camellia sinensis* (Siddiqui *et al.*, 2004). The three basic types of tea have different characteristics, including colour, aroma, taste, flavour, chemical composition, and appearance according to the extent of fermentation (Chaturvedula & Prakash, 2011). The difference is that black tea is fully fermented; green tea is unfermented; and others are partially fermented (Ho *et al.*, 2008). Black tea accounts for approximately 78% of world tea production, with green tea and oolong accounting for 20% and 2% of world production, respectively (Kamunya *et al.*, 2009). According to Mukhtar & Ahmad (2000), Western regions (North America, Europe and North Africa) and some Asian countries predominantly consume black tea, while China, Japan, India, and a few countries in North Africa as well as the Middle East drink green tea.

2.3.2 Origin and history

The purpose of this section is to provide an overview of the history of tea in the world. Tea is one of the oldest beverages known to humanity and has been grown since ancient times. As a beverage, tea's origins are traceable to areas near the source of the Irrawaddy River in Southeast Asia, or possibly further north (Kingdon-Ward, 1950). However, the exact origin or birthplace of tea is less clear, as some scholars have contended. Research suggests that tea has its origin somewhere in the Tibetan Plateau, which includes areas such as Sichuan, Yunnan, Sain, and North East India.

Tea drinking has a long history spanning over 5000 years. Its discovery dates back to an ancient Chinese legend that Emperor Shen Nung in 2737 BC was boiling drinking water under a wild tree and a few leaves from a nearby *Camellia sinensis* plant accidentally fell into a boiling pot of water and got infused. The emperor drank the beverage and found it refreshing, energizing and delicious. He experimented further and found it to have medicinal properties, as well as a pleasant flavour (Harbowy & Balentine, 1997; Weisburger, 1997; Wilson & Clifford, 1992). Thus the legendary beverage, tea, was discovered.

More evidence suggests that tea has been used in China as a folk medicine as early as the fourth century AD, and evolved to a health beverage by the end of the sixth century. As Heiss and Heiss (2007) noted, tea has been used, not only as a beverage, but also for its medicinal properties during the reign of the Shang dynasty (1766–1050 BC) in Yunnan Province. Furthermore, drinking tea was recommended to people for health benefits between 1100 BC and 200 BC. However, it was not until the Tang Dynasty (618–907 AD) that tea, long appreciated for its medicinal properties, became an object of veneration and tea trade inside China flourished. Tea has traditionally been the most popular beverage in China, and tea drinking was commonly considered to enhance blood flow, detoxify the body and to improve protection against diseases (Balentine *et al.*, 1997).

Readers may note that tea drinking remained confined to East Asia until the middle of the seventeenth century. From ancient China, tea gradually expanded to Japan and India, and further into many tropical and subtropical countries. Dutch traders first introduced tea to the European countries in the sixteenth century. While the Portuguese were the first to trade for tea in the Far East, it is, however, believed that the Dutch are the ones who popularized the drinking of tea in Europe. By the 1750s, tea was widely drunk in Britain, Ireland and the British colonies in North America. Subsequently, emigrants from Britain and Ireland to Canada, Australia, New Zealand and South Africa took to drinking tea. Eden (1965) gives a concise account of the development of the tea industry and its spread through Asia, to Africa and South America. Tea cultivation has spread to many other African countries of which the principal producers are now Kenya, Uganda, Malawi, and Tanzania. In

South America, small plantations of tea are to be found in Argentina, Brazil and Peru.

Surprisingly, it is important to note that tea was once considered a luxury product that only the noble and wealthy could afford. Today, however, it is the cheapest and most popular human beverage and enjoyed by all social classes. Tea is undisputedly a drink of choice by many people worldwide and has outpaced coffee, soft drinks, wines and liquors. Not only is tea drinking an indispensable part of daily life, but it is also an important component of multiple cultures. Tea is acknowledged in some cultures as being the key ingredient to wisdom, happiness and perfect health. There is no question that tea is being touted as a beverage of international fellowship as well as a bond that brings people together. Its significance, however, lies in the fact that it is an extremely valuable source of much needed foreign exchange in developing countries like Malawi. Furthermore, tea production is a diverse industry combining the agricultural activities of tea cultivation with the industrial factory production of "made" or "finished" tea.

2.3.3 Health benefits of tea

Much has been written about the beneficial health effects of tea. Recent research has shown that tea drinking is closely related to various aspects of human health (Blumberg, 2003; Weisburger, 1997; Yang *et al.*, 2002). There is an increasing body of scientific evidence that shows tea and its extracts as being efficacious and having positive effects on several chronic or degenerative diseases, especially cardiovascular disease and cancer (Mc Kay & Blumberg, 2002). Moreover, there is considerable evidence that moderate tea consumption lowers blood pressure and thus reduces the risk of stroke and coronary heart disease; helps prevent obesity and tooth decay; prevents and treats skin diseases as well as increases immunity. In addition, there is also a body of evidence from human studies, suggesting that tea confers protection against cancer, heart disease, and diabetes; encourages weight loss and maintenance through fat oxidation; lowers cholesterol; and brings about alertness (Hollman *et al.*, 1999; Tijburg *et al.*, 1997). Tea consumption has also been found to have a beneficial impact on bone density (Hergarty *et al.*, 2000), cognitive function (Hindmarch *et al.*, 2000), dental caries (Kavanagh & Renchan, 1998), and kidney stones (Curhan *et al.*, 1998). Furthermore, extracts of green tea containing polyphenols have also been shown to exhibit anti-HIV properties (Liu *et al.*, 2005; Yamaguchi *et al.*, 2002).

Tea is an excellent source of polyphenols, such as flavonoids, which are well known for their antioxidant properties and considered by many researchers to exert numerous protective effects. In particular, tea polyphenols include catechins and gallic acid in green tea, theaflavins and thearubigins as well as other catechin polymers in black and oolong teas (Li *et al.*, 2013). Researchers and scientists attribute tea's potential health benefits to flavonoids of which catechins are the predominant sort (Cabrera *et al.*, 2006). The major catechins are (-) epicatechin gallate (ECG), (-) epicatechin, (+) gallocatechin (GC), (-) epigallocatechin (EGC) and (-) epigallocatechin gallate (EGCG) (Liang *et al.*, 2003). EGCG is the most active of these catechins and is often the subject of studies regarding tea antioxidants. Furthermore, they (researchers and scientists) believe antioxidants protect the body by neutralizing free radicals – which are said to damage elements in the body over time and contribute to chronic disease (Chaturvedula & Prakash, 2011; Frei & Higdon, 2003).

More importantly, polyphenols are the most biologically active group of tea compounds to exhibit various health promoting biological and pharmacological activities including antibacterial (Bandyopadhyay *et al.*, 2005; Nance & Shearer, 2003), antiviral (Nakayama *et al.*, 1993; Yamamoto *et al.*, 1997), antioxidative (Matsuzaki & Hara, 1985; Mukhtar & Ahmad, 2000), anti-inflammatory (Alexis *et al.*, 1999), antitumour (Katiyar *et al.*, 1993), anticarcinogenic (Khan *et al.*, 2006; Lambert & Yang, 2003; Siddiqui *et al.*, 2006), antimutagenic (Constable *et al.*, 1996; Kuroda, 1996; Yen & Chen, 1996), antihypertensive, neuroprotective, cholestral-lowering, and thermogenic (Hayat *et al.*, 2015).

Tea also contains traces of other compounds with considerable interest for human health such as caffeine (3-4%), tannins, theaflavins (1.5-2.0%), amino acid (theanine)(2%), sugars(4%), vitamins (A, C, and E), and minerals (e.g. aluminium, fluoride, and manganese) (5%).Vitamin C, for example, not only acts as an antioxidant, but it is also an essential bioactive compound that can prevent heart disease, neuro-degenerative diseases, cancer, and hypertension (Biacs *et al.*, 1992; Lee *et al.*, 2005). Caffeine found in tea is also claimed to increase alertness, concentration and mental performance (Ruxton, 2008; Sharma *et al.*, 2014).

In addition, some studies have shown that theanine reduces mental and physical stress and produces feelings of relaxation. Further evidence also shows that theanine may keep the brain healthy and prevent memory decline in older people. It has been shown to affect areas of the brain involved in attention and complex problem solving. Most studies have suggested that tea drunk in moderation has no harmful effects on human health, however, other studies have observed harmful effects particularly when tea is drunk in excess. Higher tea consumption has been associated with side effects like hepatotoxicity, reduced iron absorption, oxidative stress or precipitation of digestive enzymes (Jain *et al.*, 2013).

To sum up, experimental and epidemiological evidence from multiple studies provide a convincing argument that moderate tea drinking may offer protection against degenerative diseases like cancer and cardiovascular diseases. In addition, moderate tea consumption is linked to reduced risk of kidney stone formation, protection against bacterial infections as well and dental caries (Gardner *et al.*, 2007; Stenevold *et al.*, 1992; Strangl *et al.*, 2006; Trevisanato & Kim, 2000; Weisburger, 1997; Yang *et al.*, 2011). However, controversies regarding the benefits and risks of tea consumption persist: but the limitless health-promoting benefits of tea outweigh its perceived toxic effects. More evidence is required before the links between tea drinking and human health can be said to be conclusive.

2.4 Malawian tea industry overview

The purpose of this section is to give a succinct overview of the tea industry in Malawi.

2.4.1 Overview

The tea industry is traditionally Malawi's third largest agricultural industry, after tobacco and sugar, and has a turnover of US$121 million (MWK90 billion), with a significant social and economic importance at national level (NSO, 2016). Tea is one of the most important cash crops in Malawi, grown on approximately 19,000 hectares (ha) or about 0.5% of the total agricultural land in the country. The Malawian tea industry contributes tremendously to total manufacturing output, foreign exchange earnings, and revenue through cess, sales tax, and corporate income tax, as well as being a productive contributor to the gross domestic product (GDP). More importantly, the industry has long been a focal point for socio-economic development of the rural areas through employment generation, income, and rural infrastructure. It is therefore clear that the Malawian tea industry will continue to be an important engine for the future growth of the economy.

Tea plantations in Malawi are mainly located in three districts: Mulanje and Thyolo (southern region) and Nkhata Bay (northern region). These districts are known to have good agro-ecological conditions for tea, such as nutrient rich soils, good rainfall exceeding 1 200 mm per year and high elevation of 600–3 000 m above sea level (TRFCA, 2015). In addition, these areas receive more than 1 200 mm of rainfall annually and are consequently less dependent on irrigation. The total land area under tea cultivation in Malawi is distributed as follows: 9 335.68 hectares (Mulanje), 8 816.11 ha (Thyolo), and 648.2 ha (Nkhata Bay) (Chirwa, 2006).

Tea is manufactured using CTC, LTP, and orthodox manufacturing processes. Nearly 80% of the tea in Malawi is predominantly produced using the LTP process. The more efficient CTC manufacturing process is not widely used in the Malawian tea industry, but it is very popular in India and East Africa. However, companies are changing over to more CTC manufacturing with a view to lower the cost of production and to achieve a better competitive position on the world market. In addition, the pace at which the change from the LTP to CTC manufactured tea is taking place, is rather slow. This is most likely due to the high cost of replacing the existing LTP roller machines with CTC rollers. Pound and Phiri (2009) observes that the Malawian tea industry is well positioned to compete on the world market due to low pest incidence and characteristics for blending, namely the bright coppery colour, which is in demand from buyers and sellers.

2.4.2 A brief history of the Malawian tea industry

The tea industry is one of the largest and oldest industries in Malawi. Its long history spans over 120 years, hence giving pre-eminence to this country as one of the most successful contributors of the tea commodity in the world. Palmer (1985) gives a concise account of the genesis and historical development of the tea industry in Malawi. Tea as a crop was first introduced to Malawi by the British in 1878 (Hutson, 1978), but commercial production began in 1891 (Ellis & Nyirenda, 1995), and has been growing since then, reaching 19,000 ha in 2013. The first tea grown in Malawi is said to have been brought from the Royal Botanic Garden of Edinburgh. Palmer (1985) observes that the commercial tea industry was not active until 1933, when it received protection from the International Trade Regulation (ITR) Scheme and was connected to the international markets through its London Committee. He further notes that the success of the Malawian tea industry did not last long as it encountered several challenges. It is said that by the end of the 1940s, the tea industry in the country was severely challenged by issues such as fluctuating prices, high costs of production, unfavourable climatic conditions and increased exposure to fierce competitive pressures because of the phasing out of the ITR protection scheme. Coincidentally, these are the same issues confronting the industry today.

Nevertheless, tea production in Malawi has been steadily increasing over time. Table 2.1 shows the trend of tea production in Malawi since 1961.The total production area grew from nearly 12,037 ha in 1961 to nearly 19,000 ha in 2013 (an increase of 58%). However, it is important to note that the surface area of planted tea has remained constant at around 19,000 ha for the last two decades. Production of made tea has risen strikingly from 14.3 million kilograms in 1961 to 46.5 million kilograms in 2013, with a record production level of 52.6 million kilograms in 2009. This is projected to grow annually at 0.8% up to 2021 (FAO, 2012). Total annual tea production over the last two decades has been oscillating between 46 and 52 million kilograms. In addition, the value of tea exports grew seven fold from US$11.5 in 1961 to US$121 million in 2014 (Figure 2.3). Productivity in the same period increased by 127% from 1080 to 2447 kg/ha. The growth in productivity is due to improved cultivars, efficient crop production and better agricultural management techniques. This growth in output is due to an increase in the surface area of planted tea, as well as expansion and modernization of some tea factories. The next section will elaborate on the economic importance of the tea industry in Malawi.

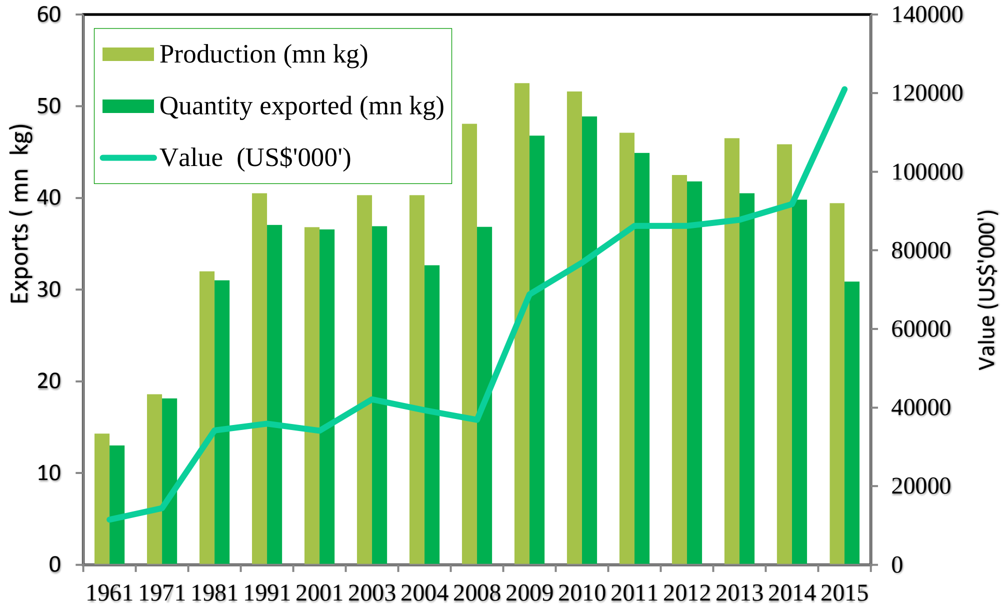

Figure 2.3: Trends of tea export volume and value in Malawi: 1961–2015

2.4.3 Tea's growing importance in Malawi's economy

The main purpose of this section is to present an overview and the role of the tea industry in Malawi's economy. The tea industry has become increasingly important in the Malawian economy since it contributes approximately 12% of the country's agricultural output, 1.5% of GDP, 7% of manufacturing value added (MVA), 11% of industrial employment, and 8% of total export earnings for the country. Tea exports generated about MWK90 billion (US$ 121 million) in 2014, making it the country's third largest foreign exchange earner after tobacco and sugar (NSO, 2011). The tea industry also provides a sizeable amount of revenue to government through direct and indirect taxes.

More importantly, the Malawian tea industry remains the largest source of formal sector employment in the country. It is a major contributor to direct employment in tea production and processing. In addition to direct employment, tea production provides indirect employment for various support industries such as fertilizer, chemical, fuel, transport and packaging industries. At present, the tea industry provides direct and indirect employment to approximately 1.5 million people through knock-on and ripple effects. Furthermore, the tea industry directly employs between 40,000–60,000 workers in tea cultivation, plucking and processing, making it one of the leading sources of livelihood in Malawi (TAML, 2014; UNDP, 2012). The industry also directly supports approximately 15,573 smallholder growers who are reliant on tea (FAO, 2016).

Another essential contribution being made by the tea industry, although one that is often unnoticed, concerns infrastructure development and environmental conservation. More recently, the Malawian tea industry has become a major provider of infrastructure, schools and healthcare for workers and communities around the estates as well as inputs and credit for smallholder producers through the out-grower contract arrangements (FAO, 2015a). Most importantly, tea production also contributes to environmental conservation through enhanced water percolation, reduced surface soil erosion, and mitigation against global warming through carbon sequestration. Thus, the importance of the tea industry in the country's economy and environment is very significant and is expected to increase over the next few years. The next section will provide the reader with information on how the tea industry is structured.

2.4.4 Structure of the Malawian tea industry

Tea production in Malawi has traditionally been associated with large private estates (plantations) controlled by a handful of multinational companies. However, nowadays smallholder growers (out growers) are increasingly becoming important in the industry as well. Large private estates account for 85% of land under tea and 93% of production, with roughly 15,573 out growers (with land holding size ranging from 0.1 to 3 ha, and an overall average plot size of 0.25 ha per small holder tea grower) providing the other 7% (Pound & Phiri, 2009). There is considerable scope for smallholder farmers to expand production, largely due to the inability of estate production and land to be expanded any further. Currently, production by small holder farmers is about half of estates due to low bush density (6,000–8,000 plants/ha), as opposed to estates (15,000 plants/ha), suboptimal fertilizer use, less frequent plucking, lack of irrigation and time to weed fields regularly (Pound, 2013). These challenges represent an opportunity to increase smallholder yields and productivity. Average yield is considerably higher in the estate sector (2,465 kg/ha) compared to small holders (1,049 kg/ha).

The tea industry in Malawi currently comprises 11 privately held companies, owning 44 estates and operating 21 tea processing factories (16 owned by UK based companies, and 5 by locally owned enterprises). These units process more than 220 million kilograms green leaf annually. The tea crop can produce up to approximately 46 million kilograms black tea annually. Evidence shows that on average, 99% of the tea production in Malawi is exported while 1% is consumed domestically. More recent statistics from the National Statistical Office (NSO) indicate that the Malawian tea industry generated MWK 90 billion (US$121 million) in export earnings (NSO, 2016). The tea industry is also characterized by a dichotomy of very small to relatively large factories, with a preponderance of medium units, as well as factories with modern technologies and those with obsolete technologies.

Table 2.1: Tea production trends in Malawi during the past 50 years

	Tea Area		Tea Production		Yield
	(ha)	(%)	Tons	(%)	(kg/ha)
1961	12,037	1.22	13,000	1.45	1,080
1971	15,455	1.09	18,157	1.42	1,175
1981	18,423	1.65	31,017	1.69	1,684
1991	18,300	0.84	40,530	1.54	2,215
1992	18,587	-	28,136	1.15	1,514
1993	18,705	-	39,497	1.55	2,112
2000	18,782	-	42,114	1.45	2,242
2001	18,761	0.71	36,587	1.2	1,960
2002	18,800	-	39,185	1.28	2,084
2003	18,694	-	41,693	1.31	2,230
2004	18,663	0.67	32,672	1.17	1,750
2008	19,000	0.55	36,861	1.24	1,940
2009	19,000	0.54	52,559	1.3	2,800
2010	19,000	0.52	51,591	1.18	2,715
2011	19,000	0.49	47,056	1.02	2,477
2012	19,000	0.47	42,490	0.89	2,236
2013	19,000		46,500	0.92	2,447
2014	19,000		45,855		2,413
2015	19,000		39,467		2,077

Source: TAML (2016), FAO (2015b) and author's calculations

2.5 Challenges and opportunities

This section aims to identify major challenges and opportunities that will contribute to the development of a decision-making tool to assess sustainable performance in the tea industry. Tea production still remains an important industry and confers significant social and economic benefits to Malawi. However, the industry has increasingly faced numerous challenges that affect not only its competitiveness, but also the sustainability of production. Rising production costs, low productivity, rapidly aging tea bushes, low value addition and product diversification, and changing weather patterns are the major issues that need urgent attention for the Malawian tea industry's survival in the global competitive market (Table 2.2). In addition, regulatory pressures, technology changes, and the need to constantly adapt its business models are threats of emerging importance. Many academic writings, conference papers and journals discuss major issues and challenges faced by the global tea industry. The following sections review and highlight the key challenges facing the Malawian tea industry.

Table 2.2: Summary of tea industry challenges from empirical studies

Challenge	Description
1. Rising cost of production	- Rising cost of production (spiralling cost of labour and farm inputs) - Farm productivity in terms of yield per hectare - Inflationary pressure - High cost of replanting and modernization of tea factory machinery
2. Low productivity	- Low tea yields due to climate change, soil fertility, ageing of the tea shrub, high operating expenses, poor farming practices, low rate of replanting - Less land productivity and inefficient labour use
3. Low product diversification	- Dependence on low quality bulk tea - Lack of diversification (lack of value-added products for other markets)
4. Heavy reliance on few export markets	- Over-reliance on few export markets - Untapped local market potential
5. Quality	- Perceived low quality - Lack of quality improvement in industry due to high demand for low price and low quality tea from the international markets
6. Old and obsolete machinery	- Lack of capital for factory modernization - High cost of modern tea machinery - Low profit margin
7. Ageing of plants	- Ageing of tea bushes and slow pace of replanting
8. Climate change	- Changes in annual rainfall patterns - Erratic changes in temperature
9. Price volatility on the world markets	- Rising cost of production - Stagnating or falling down of world tea prices - Global supply exceeding demand

a) Rising cost of production

Rising cost of production resulting from an increase in the cost of labour and farm inputs has been a primary cause of concern for the tea industry. While market prices for tea have been falling, the cost of production has been on the rise, exerting enormous pressure on the tea industry's profitability and income. Among the factors identified as giving rise to the high production cost is labour, which varies from 55 to 73% of the overall cost of production, and approximately 75% of that labour cost is for tea plucking (Wal, 2008). In addition, the spiralling input cost of electricity, fuel, fertilizers, pesticides, machinery, packaging materials, together with dilapidated infrastructure, including transportation, result in the high cost of production (Wal, 2008).

Moreover, farm productivity in terms of yield per hectare is also another major factor contributing to the high cost of production. As is widely known, the yield per hectare of a tea field is affected by change in climate, soil fertility, ageing of the tea shrub, high operating expenses, and poor farming practices among others. The stagnation in productivity in the Malawian tea industry is compounded by high land-labour ratio. Furthermore, farm as well as factory labour productivity of the industry is considerably low. Presently, inflationary pressure is also pushing fixed costs further. Additionally, the high cost of replanting and modernization of tea factory machinery also pose a significant challenge to the industry.

b) Low level of productivity

Low productivity is another severe challenge faced by the Malawian tea industry. The productivity performance of this industry is on the decline owing to the fact that the cost of production has risen exponentially on the one hand and the prices of tea have remained mostly stagnant or have declined. In addition, tea yields are relatively low and below their technical potential. The low yields are mainly attributable to technical and management factors, particularly cultivation of non-improved varieties, and deficiencies in crop management, including fertilizer application, pests and disease control, and total rainfall. De Jong (1997) attributes the low productivity, estimated at 60%, to less land productivity and inefficient labour use. Further, the low tea yields are largely influenced by change in climate, soil fertility, ageing of the tea shrub, high operating expenses, poor farming practices and low rate of replanting, to cite but a few (Shyamalie & Wellala, 2012). Moreover, the low yields have resulted in inadequate supplies of the harvest (green leaf) to tea factories, leading to a low level of factory capacity utilization. This, combined with low green leaf quality and processing inefficiencies, has resulted in high costs of tea manufacture. These factors have contributed to a low level of profitability in tea processing. Consequently, the overall productivity and profitability of tea production and processing in Malawi are rather low.

c) Value addition of tea (or low product diversification)

Insufficient product diversification is another problem of the Malawian tea industry. Over the years, the country has relied on production and export of low quality bulk tea (in semi-processed form), which has been traditionally used as a raw material (filler) to blend with “the often perceived” high quality teas from other countries. The industry has not produced any other value-added products for other markets like flavoured teas, green tea or coloured tea. In order to develop the Malawian tea industry, there is a need for tea companies to diversify and invest in the production of a variety of branded tea products. Companies are being urged to diversify into other tea products, which include the processing of tea extracts for pharmacological use, processing of convenient fast moving consumer goods like ready-to-drink beverages, juice blends and wines.

d) Heavy reliance on few export markets

Over-reliance on few export markets is also a major concern in the tea industry. The country’s tea exports are concentrated in a few export markets. The United Kingdom (UK) accounted for 35% of the total tea exports and the share of Europe was 40% in 2013. South Africa, Kenya and the United States of America (USA) accounted for 32%, 11% and 8% of total exports respectively. More than 10 countries, including India, Pakistan, Canada, China, Australia, Botswana, Zambia and Egypt accounted for the balance of 14%. Even though the UK and South Africa accounted for close to 70% of Malawi’s tea exports, the country supplies only 20%

and 50% of UK and South Africa tea markets, respectively (DAFF, 2014; Ecobank, 2012; EDB, 2012). Clearly, Europe and Africa offer a massive, yet highly untapped market for Malawi's tea. There is still a huge local market for tea, which remains untapped.

e) Tea quality

A major challenge that affects negatively on the profitability of the Malawian tea industry is quality. The Malawian tea industry has earned a reputation for producing low quality tea, with a bright coppery colour that makes it suitable for blending with high quality teas, mainly from Sri Lanka and Kenya. However, due to the perceived low quality of Malawi's tea, the export prices of the country's tea are considerably low compared to international prices. In addition, the tea industry appears not to focus on improving the quality of the finished tea, largely because of the existing high demand for low priced and low quality tea from the international markets. As a result, tea producers in the country continue to be paid substantially low prices for this tea. This makes it almost impossible to maintain the plantations. To ensure its survival, it is obvious that the tea industry has to find foreign markets, and that this will require a vast improvement in quality of Malawi's tea.

f) Old and Obsolete machinery

The tea industry in Malawi has been seriously undermined by continued use of old and obsolete machinery and equipment. This is, in part, because tea firms cannot carry out modernization for lack of capital. The inability to timely modernize the equipment and machinery has led to the decline of the industry's competitiveness. Modern tea machinery is known to be more automated, efficient and cost effective. However, these machines have been found to be costly and require technological skills and ongoing support. As a result, tea firms in the country have been reluctant to shift their business processes to modern technologies due to the huge investments required. Furthermore, the low profit margin being experienced in the industry has prevented tea firms from replacing the old technologies with modern ones. Consequently, they cannot compete with those having modern and efficient systems in place, and therefore financial and technical assistance is imperative to make them viable.

g) Ageing of plants and slow pace of replanting

Ageing of tea bushes is a major problem faced by the tea industry in Malawi. It contributes to a low rate of production and quality degradation. More importantly, it is one of the factors that influence productivity. Numerous studies have examined the relationship between the age of tea plant and productivity (Dutta *et al*., 2010). These studies have found that productivity of tea begins to decline after 30 years of age. In other words, after 30 years of age, the tea plant becomes uneconomic because of aging and thus requires replanting. Most of the tea bushes in the country are as old as 60 years and their productivity is therefore relatively low. Towards this end, it is imperative for the tea industry to replant with new tea plants to rejuvenate land productivity. Despite these efforts, the rate of replanting in the Malawian tea industry is unknown.

h) Climate change

Climate change has emerged as a major challenge facing the tea industry in Malawi. Changes in annual rainfall patterns or erratic changes in temperature, which result in long drought periods and flood conditions in tea fields, have been rampant. This adversely affects production, quality and market price of the produce. Climate change has also led to increased pest infestations, leading to severe crop loss as well as subsequent drops in productivity. Consequently, the tea industry continues to incur additional costs because of irrigation, since climate change is affecting rainfall patterns.

i) Price volatility on world markets

World tea prices have long been stagnating or declined while cost of production has been rising, putting pressure on tea producers. Consequently, producer margins have exhibited a declining trend in recent years, largely due to rising cost of production and stagnation of tea prices. The decline in price has been primarily due to an increase in production, notwithstanding sluggish demand. The world market for tea has been in marginal over-supply over the years as yields per hectare have risen without a corresponding increase in worldwide demand. The increase means that prices have fallen in real terms despite husbandry and efficiency improvements. Mulder (2007) observes that in real terms, prices of tea have declined by about 35% in the last three decades. Thus, the tea industry has seen no increase in real terms. This has affected both tea growers and the nation in many ways. Low prices for tea affect the income of plantation workers in tea estates as well as that of smallholder tea growers.

2.6 Environmental and social impacts

This section summarizes the most important environmental impacts associated with tea production in Malawi. The tea industry has been playing a critical role in the country's economy. Not only does it generate the much-needed foreign exchange to the country, but also provides the livelihood to a large number of people, directly and indirectly. However, the tea industry has undoubtedly been proved as one of the sectors that consume large amounts of energy, produce numerous organic pollutants and cause serious contamination. In addition, the Malawian tea industry is now linked to the destruction of natural forests; loss of biodiversity; high-energy consumption; soil, air and water pollution; as well as violation of labour laws – child labour, forced labour, extremely low wages, and dangerous and harsh working conditions. Consequently, it is under growing scrutiny from the public.

2.6.1. Major environmental concerns of tea production

The environmental impacts associated with tea production are elaborated on hereunder.

(a) Habitat conversion for tea cultivation

Clay (2003) argues that habitat conversion in general, and associated biodiversity loss, is one of the major negative environmental impacts resulting from the tea industry. Tea is often cultivated in plain, hill and mountain areas of the country, which tend to be areas with highest biodiversity. Conversion of farmland and primary forests into tea plantations contributes to species reduction. In addition, since tea is typically cultivated on sloping land, considerable soil is lost before the plantations are fully established to protect the soil. Moreover, tea is usually grown under rain-fed mono-cropping systems, which drastically decreases biodiversity through loss of plants and animals. Monocultures also provide a perfect environment for pests, resulting in an increased use of pesticides, but there is no empirical evidence to support this assertion.

(b) Deforestation

Tea production also triggers deforestation and environmental degradation in Malawi. The harvesting of firewood from local forests for tea drying causes deforestation, which contributes to loss of biodiversity in terms of plant and animal species, as well as soil erosion. Notably, deforestation is not supposed to be an issue in the Malawian tea industry considering that wood fuel used in some factories is sourced from *Eucalyptus*, grown on the tea planters' own estates. However, since not all tea factories have sustainable plantations from which they would harvest wood fuel, natural forests remain the major source.

(c) Energy consumption

The tea industry is extremely energy intensive, requiring between 4 and 18 kWh of energy to process 1 kg of dried tea, comparing to 6.3 kWh for a kilogram of steel (Wal, 2008). Depending on process and equipment efficiencies, energy is one of the main cost factors, accounting for an average of 25% of the total processing costs, reaching figures of 40% in certain factories (UNEP, 2006). Sources of energy used in tea production include firewood for steam generation; electricity as a common source of power for motors and machine drives, conveyors, fans, and pumps as well as building operations such as lighting and ventilation systems; and diesel for running diesel generator (DG) sets when supply from the national grid is unavailable. Electricity accounts for 15% of the total energy requirements, while the rest (85%) is thermal, being used for withering and drying of tea (AIT, 2002).

Drying puts enormous amount of pressure on the environment, as it requires large amounts of firewood, sourced from natural forests or planted forests (Clay, 2003). Eucalyptus is the common tree species used in the factories. However, this tree species is also known to consume groundwater, a concern that is enhanced when grown in large proportions. Diesel combustion in machines such as tractors, vehicles and standby generators highly pollutes the environment through emission of greenhouse gas and other pollutants, and is therefore a matter of concern. Energy use in the Malawian tea industry is still highly inefficient, with more possibilities for improvement. Continued use of old and obsolete machinery and equipment has contributed to tea factories being inefficient in energy use. Added to this is the perception that energy costs represent a relatively small fraction of the total production costs. Hence, energy efficiency has not been given the prominence it deserves in this industry.

(d) Agrochemical use in tea

Tea consumes substantial amounts of inorganic fertilizers and pesticides, which have serious environmental and health impacts. These chemicals are added to protect tea bushes and to enhance productivity (Sood *et al.*, 2004). Inorganic fertilizers typically supply macronutrients like nitrogen (N), phosphorus (P) and/or potassium (K) as well as micronutrients such as sulphur (S), iron (Fe), manganese (Mn), copper (Cu), boron (B) and zinc (Zn). These elements are mainly supplied in the form of inorganic salts such as urea, phosphate, boric acid, sulphate of ammonia, etc. However, the nutrients in the fertilizer are not entirely taken up by the crop, but distributed into the surrounding environment.

Excess nutrients and trace metals associated with fertilizers are distributed from tea fields in run-off rainfall, which affects the quality of groundwater, rivers and streams that flow into estuaries and coastal environments. In addition, excess nutrients in watercourses often lead to the growth of algae – some of which are toxic – resulting in aquatic life being destroyed. Moreover, increased application of inorganic nitrogenous fertilizers, such as urea and sulphate of ammonia, contributes significantly to acidification, contamination of ground and surface water, and enhanced greenhouse gas emissions.

Pesticide use in tea production has been linked to severe negative environmental and social impacts. Whilst tea production in Malawi has been claimed to be relatively pest-free, there are still some companies that use herbicides for chemical weeding. The study noted that insecticides are only used on tea when need arises. This is a matter that cannot be casually dismissed; hence, it cannot be safely concluded that pesticide use is non-existent in Malawi. As with fertilizers, the tea plant does not absorb these chemicals, rather, they dissolve in run-off water and ultimately contaminate rivers, wetlands, and groundwater. The toxic properties of these chemicals may kill wildlife directly or accumulate to fatal levels in the ecosystem. Furthermore, the use of pesticides in the tea industry has also resulted in health concerns among tea growers and consumers. Direct exposure to the chemicals by workers is well known to potentially have long-term effects on the health of workers or farmers. However, there is surprisingly little information on the use and environmental impacts of agrochemical use in the Malawian tea industry.

(e) Soil erosion and land degradation

Soil erosion and land degradation are important issues in the tea industry in Malawi as they affect its long-term sustainability. Tea is currently grown on many steep slopes and hills, contributing to comparatively high rates of soil erosion, resulting from the increased rates of water run-off on sloping land. Loss of soil by erosion is unquestionably a major problem that can affect future yields and ultimately limit the sustainability of tea production. Soil erosion also represents an environmental threat since sediments from eroded soils and nutrients from applied fertilizer often foul or pollute rivers, streams, estuaries and marine ecosystems.

Tea cultivation, particularly in land laid bare in preparation for planting, strips it of any protective cover allowing the soils to dry out. This affects overall microorganisms' diversity and mass, both of which are essential to soil fertility. Additionally, exposed topsoil is easily washed away on sloping land, with nutrients leached from the soil. Furthermore, the continued removal of tea from the fields gradually reduces fertility and forces growing to increasingly rely on fertilizers. Continued use of the same plot for a single crop also negatively affects soil fertility (Clay, 2003). Consequently, chemical fertilizers are applied to make up for this loss. This in turn results in a negative spiral in which increasing amounts of agrochemicals are needed to maintain production in inverse proportion to the decreasing soil quality. Expensive fertilizers and pesticides increase field costs estimated at 35% (43% attributable to fertilizers) and decrease profitability of tea companies.

(e) Waste production

The tea industry in Malawi generates many waste streams, including wastewater, atmospheric emissions and solid waste, which are not potentially hazardous. Solid waste produced in tea factories includes dust from packing and sorting areas; dry leaves from the weighing section; leaf spillages from both the withering stage and at the offloading area; and fibres blown off from dryers, as well as soot and ash from steam boilers. Solid wastes account for 0.68% (roughly 1%) of made tea production and do not pose any major threat to the environment (Taulo & Sebitosi, 2016). However, waste production is also one of the biggest threats to the environment. Combustion of fuel (firewood and diesel) in steam boilers and standby diesel generators contributes to air pollution (AIT, 2002).

In addition, wastewater from rolling and continuous fermentation units is one of the most important sources of pollution, and accounts for 1.8% of made tea production (ibid). Wastewater generated predominantly from cleaning processes in the tea factory contains high amounts of agents causing damage to the environment, including suspended and dissolved solids, chemical oxygen demand (COD), biological oxygen demand (BOD), colour and aroma. For example, an empirical analysis of wastewater from tea factories in Malawi found that BOD levels measured 335 mg/L compared to the national standard of 20mg/L.

Similarly, in Kenya, BOD levels measured 150 mg/L while the COD level measured 505.5 mg/L against recommended maximum discharge limits of 30mg/L and 50 mg/L, respectively (Oirere *et al.*, 2013). This is an indicator that effluent from tea factories has a detrimental impact on water quality parameters, and therefore should not be casually dismissed. Higher values of COD and BOD in the effluent are known to cause depletion of dissolved oxygen, which has an adverse effect on the aquatic ecological system. At present, most tea factories lack effluent treatment plants, but some have constructed wetlands for biological treatment of wastewater, while others discharge into nearby rivers, causing pollution.

2.6.2. Social impacts

In addition to the negative environmental effects, the tea industry is also plagued with several social issues. This section focuses on five themes intimately related to the tea industry: poor working conditions, child labour, low wages, labour casualization, and sexual harassment and discrimination.

(i) Working conditions (health and safety)

Working conditions in the tea plantations is hostile and major health risks exist for the workers in the tea fields. Not only is tea plucking (picking) difficult, but it is also hazardous. Tea pickers, the majority of whom are women, are on their feet all day (8 to 12 hours), carrying tea collecting baskets on their backs. Aching shoulders and backs are therefore common. Wal (2008) reports that tea pluckers are sometimes exposed to harsh weather conditions (cold, hot, or wet). They are also vulnerable to pesticides, mosquitoes and other insects, and poisonous snake bites, often with limited physical and medical facilities. According to the International Labour Organization (ILO), 60–70% of respiratory and water-borne diseases affecting tea plantation workers are due to inadequate sanitation in the tea industry.

In addition, working conditions such as clean water, rest rooms and food storage facilities are usually absent in tea fields. Workers also face the risks of accidents due to the uneven terrain and steep slopes on which tea is picked. Consequently, fractures due to falling from heights are becoming more common. An average of 86 accidents are reported each year per company, with a minimum being 55 and maximum 162. Furthermore, there is often exposure to pesticides and insecticides, which the ILO cites as one of the major health and safety hazards tea workers face. Workers use pesticides spraying equipment with poor or no protection, leaving the workers vulnerable to the effects of both acute and long-term exposure to the chemicals.

Moreover, there are indications that the majority of workers, because of illiteracy, do not know the number of hours they work per week, with most of them working between 60 and 72 hours a week. In addition, when harvests are high during the rainy season, overtime is compulsory for factory workers. Workers can be forced to put in as many as 72 hours a week against the ILO threshold limit of 56 hours per week.

(ii) Low wages

The tea industry in Malawi is also exploitative. At present, wages paid in this industry are woefully low, and often below the living wage. The cost of production represents 55 to 73% of made tea production costs, with plucking (picking) accounting for approximately 75% of these costs (Wal, 2008). The daily target for each plucker is 44 kg and this attracts a daily wage between MWK850 (US$1.13) and MWK950 (US$1.27), which compares with a legal minimum wage of

MWK850 (US$1.13). However, the minimum wage level is below the living wage of MWK1193 (US$1.59), and, therefore, fails to provide the worker and his/her family with a decent living (Anker & Anker, 2014).

(iii) Discrimination against women

Discrimination against women in the form of sexual harassment has been identified by workers interviewed as a major violation women face in the tea industry in Malawi. Women working on tea estates are commonly subjected to sexual abuse and discrimination. They are coerced into sexual relationships with their superiors, in exchange for favours such as better payment or promotion; and refusal can lead to repercussions, such as being allocated too much work or being sent to work in lonely or dangerous plucking zones. This study found that some managers demand sex as a precondition for employment. These women often carry the fear of pregnancy and/or sexually transmitted diseases silently, as these issues are seldom discussed in public and most of them go unreported. Failure of the tea industry to employ women in management positions is another form of discrimination. Additionally, cases exist where women who fell pregnant have had their jobs terminated and also lost their terminal benefits, such as pension and gratuity.

(iv) Casualization of labour

Labour casualization is also one of the major social issues that require redressing. The tea industry employs two categories of labour, namely temporary and permanent. The majority of workers in the tea industry are temporary because of the seasonal nature of the tea business. In addition, employing temporary workers is found to be inexpensive compared to permanent ones. However, casualization of labour is a serious matter of concern as it is associated with several disadvantages including low pay; lack of job security and benefits that permanent workers accrue, such as pension benefits, access to medical care for their children, etc. Wal (2008) observes that “since most workers are hired as temporary labour, they have poor job security in the event that they face some personal issues such as bad health that inhibits them from working”.

(v) Child labour

Child labour is a significant social problem that has attracted increasing attention in recent years. Past research has confirmed the prevalence of child labour in the tea industry although formally and legally employing a child is prohibited in Malawi (Chirwa, 2006; Eldring, 2003; Phoso, 1995). Findings of these studies indicate that child labour in the country can be explained by poverty, lack of resources (especially educational, etc.), and poor institutional and regulatory settings (Eldring, 2003). However, lack of comprehensive statistical data and the inadequacy of specific studies make it difficult to determine the magnitude of the problem. In addition, the accurate estimation of overall magnitude of child labour (either from a qualitative or quantitative point of view) is virtually impossible due to the predominance of informal and unorganized nature of the labour market. Further, the problem of estimating the child labour becomes even more complicated because of the multiplicity of concepts, modes of measurement, methods of research, and the sources of information for data collection.

While accurate systematic data is lacking, there is clear evidence that child labour does exist in the tea sector, contrary to claims by the Tea Association of Malawi that child labour has declined significantly. TAML purports that tea estates no longer hire anyone younger than 18 years. This is a policy for all tea estates dictated by TAML – its employee practices and procedures that all tea estates are compelled to follow. However, results of this exploratory study shows the existence of child labour down the value chain in the cooperatives and smallholder family farms. This study recommends that tea companies in partnership with the cooperatives and smallholders adopt an integrated child labour monitoring system to reduce child labour through their entire supply chain. The study further recommends that tea companies collaborate with other stakeholders, especially Oxfarm, Action Aid and Plan Malawi, in an effort to contain child labour. In addition, tea companies must share best practices in terms of organizational structures and ways to stop involvement of children in the cooperatives where they source their tea.

2.7 Chapter summary

This chapter provides background information on the tea industry in Malawi, its structure and economic importance, and identifies major challenges as well as its environmental and social impacts. The purpose of this chapter was to describe the existing situation of the Malawian tea industry. It highlights the major trends and shifts in relation to the sustainability concept and reveals how the tea industry can cope with market shifts and challenges with the help of multi-objective optimization modelling. The chapter is based on a review of various studies conducted earlier as well as the analysis of secondary data. The findings of the study are as follows:

The analysis of the tea industry in Malawi concludes that the tea industry is positively contributing to economic growth, value addition, employment and wealth creation. The Malawian tea industry contributes approximately 8% of total export earnings for the country and generates over MWK90 billion (US$121 million) annually. Tea trading constitutes approximately 1.5% of total GDP and accounts for 12% of the country's agricultural output, and 7% of manufacturing value added (MVA). Moreover, the tea industry is a major employment sector of the economy, with 50,000 people (11% of the workforce) employed directly in production or indirectly in tea-related activities, such as fertilizer, chemical, fuel, transport and packaging industries; thereby providing livelihood to approximately 1.5 million Malawians. The country is also a major trader of tea on world markets. It ranks thirteenth among tea producing countries, with a share of 2–4% in total world markets.

The results of this chapter indicate that, over the past five decades, the tea industry in Malawi has experienced tremendous growth in terms of harvested area, production, and yields. Area planted with tea has grown substantially from 12 037 ha in 1961 to 18 000 ha in 1981, and, thereafter, stagnating between 18 500 and 19 000 ha. However, the country's share of global tea harvested area has declined from 1.22% in 1961 to 0.47% in 2013. Production of made tea increased from about 14.3 thousand tons in 1961 to the present level of 46.5 thousand tons, down from a record production level of 52.6 thousand tons in 2009. However, tea productivity is considerably lower for a smallholder (1,049 kg/ha) compared to the large estate (2,465 kg/ha). The wide gap in tea productivity implies that there is significant scope for increasing tea production by raising yields on smallholder tea farms. This is attributed to cultivation of non-improved varieties, and deficiencies in crop management, including fertilizer application, pests and disease control and rainfall. The low productivity is a major constraint to the expansion of the tea trade, hence leading to high costs of production. Consequently, there is a need to raise productivity of land and labour.

Focusing on Malawi, this chapter also examined the major challenges confronting the tea industry worldwide. The review shows that the tea industry in Malawi is now facing numerous challenges, the most important of which remains high cost of production and low productivity. The industry has been crippled to a great extent by high production costs; low productivity; rapidly aging tea bushes and low replanting rate; low value addition and product diversification; low product quality; heavy reliance on few export markets; changing weather patterns; and a lack of new investment in machinery and equipment. This has led to hindrances in the growth of the industry. In addition, regulatory pressures, technology changes, and the need to constantly adapt its business models are threats of emerging importance.

More importantly, key sustainability issues facing the Malawian tea industry can be summarized as poor working conditions (low job and income security); child labour (especially on smallholder plantations); sexual harassment and discrimination; low wages; high use of agrochemicals (fertilizers and pesticides); inefficient energy utilization; biodiversity loss; soil erosion; deforestation; waste generation; and atmospheric pollution. A key conclusion drawn from this study is that sustainable production is not yet a standard practice of the Malawian tea industry and that assistance is needed to implement and manage sustainable production.

In order to make the Malawian tea industry a globally competitive one, drastic changes are necessary. There is a need to draw a number of initiatives in order to maintain its position on the global market and tap the potential market by enhancing the quality of its tea. The tea industry also needs to come up with appropriate strategies, aimed at value adding and reducing production costs. Potential for increased value addition and product diversification in the tea industry exists. There is a clear need for the development of a wide range of tea products to meet the growing and changing needs of the market. The tea industry in Malawi has to increase the capacity of utilization and provide tea factories through investment in modern tea machinery and equipment with greater processing efficiency. This would substantially reduce operational costs. The next two chapters provide the theoretical framework for the study.

Chapter-3
Literature Review

3.1 Introduction

The central aim of the research, which underpins this thesis, is to develop a multi-objective optimization tool to support decision-making processes in the Malawian tea industry. This chapter provides a review of the relevant extant literature on two main topics that frame the domain of this study. The purpose of this chapter is to review the state-of-the-art in sustainability and productivity. This chapter is divided into six sections. The chapter starts with a discussion of sustainable production as a new paradigm shaping the manufacturing industry. The third section discusses the main concepts and definitions around sustainability. The fourth section provides details of drivers and benefits of implementing sustainability in the industry. The following section reviews literature on tools and methods to measure, evaluate and report sustainability based on indicators and metrics. Sustainability assessment methods and tools such as life cycle assessment (LCA) and analytic hierarchy process (AHP) are discussed in this section. The sixth section contains a brief discussion about indicators and metrics as well as criteria for selecting sustainability indicators. The sixth section introduces the concept of manufacturing productivity. Finally, the chapter concludes with a discussion of key themes emerging from the literature review.

3.2 Sustainable tea production: a new manufacturing paradigm

Sustainable production is a new manufacturing paradigm with increased significance in the tea industry. It enables manufacturing companies moving in the direction of competitiveness to meet the challenges facing the industry. Adopting sustainable production practices offers manufacturers a cost-effective route to improve their economic, social and environmental performance. Undoubtedly, it has become a new approach to decision-making in business and is receiving increasing attention from researchers and industry. Consequently, tea companies are becoming increasingly aware of the critical importance of pursuing sustainable strategies and practices. Therefore, it is not surprising that more companies are actively integrating sustainability principles into their businesses. However, the challenges of implementing sustainability are still quite significant.

This study argues that one of the key challenges facing practical implementation of sustainability in the tea industry is the lack of appropriate, easy to understand and low cost tools for implementing and monitoring sustainable performance. While the importance of sustainability is widely recognized, the concept is not as yet a standard practice of the global tea industry. In addition, the practical means to achieve this at plant or organizational level are still unclear. Although literature on sustainability is abundant and growing, very few studies have actually integrated sustainability into the manufacturing practice. Additionally, literature dealing simultaneously with the interaction between all the three components of sustainability is extremely sparse. This study attempts to fill some knowledge gaps in sustainability literature.

Traditional productivity theories and practices mainly focus on the economic performance of an organization and little or no attention is paid to aspects of the environmental and social responsiveness. On their part, environmental activist groups only focus on issues of the natural environment while social groups and labour unions also have a single focus. Admittedly, a number of good corporations have reasonably good labour and environmental practices, but they do not have structured performance strategies that are similar to their financial models. Modern corporate governance, however, demands chairpersons of boards to submit triple bottom-line returns at their shareholders' annual general meetings. The productivity solutions aimed at this research will be arrived at by using a triple bottom-line approach. This chapter argues that sustainability and productivity are intertwined and that they should be pursued together.

3.3 The concept of sustainability

Sustainability is an evasive, multidimensional and multifaceted, but widely acknowledged concept (Redclift, 1987). However, there is no universally accepted definition or assessment technique of sustainability. Consequently, many definitions appear in the sustainability literature. To put it bluntly, sustainability covers a complex range of ideas and meanings. In addition, the concept has attracted a variety of comments, views and descriptions by scholars, professionals and policy makers worldwide. Many scholars have argued that the concept in itself is vaguely defined, ambiguous, and open to much interpretation (Mozaffar, 2001; Warner, 2007). Criticisms have also been made about the proliferation of too many definitions of sustainability, with concerns for lack of operative definitions to guide decisions. There has also been a considerable debate over "what should be sustained" (Redclift, 1993; Sachs, 1999), with some researchers expressing lack of clarity in terms of "emotional commitment" (Solow, 1992), while others describing the concept as "confusing, fraught with contradictions, and just another development truism" (Redclift, 1987). At its most extreme, some scholars even argue that the concept remains problematic, nebulous and elusive (Gladwin et al., 1995; Marshal and Toffel, 2005).

3.4 Drivers and benefits towards sustainable production

This section discusses the drivers and benefits of sustainable production. Various studies have identified a few motivations of firms adopting sustainable production in their supply chain. They include competitive advantage, cost saving, greater efficiency, profitability, positive corporate image and reputation, differentiation strategy, environmental performance, and internal organizational improvements (Barney, 1991; Siegel, 2009). Growing concerns for society and environmental issues such as non-renewable resource depletion, waste generation, high energy consumption, greenhouse gas emissions, and climate change; stricter government regulations; stakeholder pressures; and economic profit, among others (Epstein, 2008). Cost efficiencies, reputation and image, and employee motivation and retention are also increasingly becoming major drivers for the implementation of sustainability in the global manufacturing industry.

Moreover, there are sufficient case studies to demonstrate that implementation of sustainable production can provide several advantages and benefits for organizations. Nidumolu *et al.* (2009) claim that sustainable production offers companies opportunities to save costs (by limiting waste and consumption of natural resources); increase efficiency; create new businesses (through environmentally friendly product innovations); and enhance brand value and reputation with customers and partners. Mc Williams and Siegel (2001); (Szekely & Knirsh, 2005) emphasize that the concept has potential to gain a competitive advantage and to generate profits. These studies suggest that companies that have embraced sustainability outperform their peers. Satterfield (2009) points out that some companies perceive sustainable production as an opportunity, investment, and pathway to innovation. Haanaes *et al.* (2011) argue that companies pursuing sustainability can gain significant benefits in the form of greater efficiencies, the ability to innovate, increased profits, and business growth. Jayaram *et al.* (2012) assert that developing and promoting sustainable business practices help businesses increase their profits because it positively affects customers' perception and actions. Gunasekaran and Spalanzani (2012) stress that sustainable practices reduce risks, avoid or reduce waste generation, increase material and energy efficiency, and innovate by creating new and environmentally friendly products and services.

Reeves and Deimler (2011) stress the importance of sustainability and encourage firms to keep abreast with changes around them and act quickly to refine or reinvent the business model of their industry. Therefore, to become sustainable in their operations, tea companies must embrace and adapt to improve their social and environmental performance, while remaining economically competitive. In addition, they have the opportunity to leverage the sustainability notion and initiatives to drive innovation, establish leadership, improve stakeholder relations, and compete more effectively. To remain competitive and adapt to the emerging challenges of globalization, firms need to respond to demand fluctuation, competition, and new market opportunities. Moreover, they need to make necessary process improvements with respect to cost, resource utilization, quality, waste generation and safety, among others. This requires companies to increasingly pay attention to achieving high performance through enhanced efficiency, productivity and quality.

Epstein (2008) argues convincingly that, in order to remain competitive, companies must incorporate environmental, social and ethical aspects in their production processes; respond to emerging challenges by engaging its many different stakeholders and addressing their concerns; and implement programs at a minimum to appease stakeholders and keep pace with peers in the industry. Furthermore, the industry must also be equipped with tools to measure, assess and evaluate its sustainable performance and to demonstrate continuous improvement in the long term. There is thus a growing need for developing systematic methods and tools that will allow companies to pinpoint potential measures to improve operations and processes as well as to quantify and simultaneously optimize their key economic, environmental and social performance.

3.5 Sustainability measurement tools

This section focuses on and presents a descriptive summary of these methods used in this study to model and calculate the environmental performance of the Malawian tea industry.

3.5.1 Life Cycle Assessment (LCA)

To fully comprehend the overall environmental performance of the Malawian tea industry, an assessment of the production and manufacturing processes with a life cycle perspective is necessary. Life Cycle Assessment (LCA, also known as life cycle analysis) is a tool for systematic evaluation of the environmental impacts of a product, process, or activity throughout its life cycle (ISO 14040, 1997). According to (Azapagic & Clift, 1999a), LCA is performed for the purpose of: (i) quantifying and evaluating the environmental impacts associated with a product, a process or an activity from "cradle-to-grave," which assist decision-makers to choose between alternative products and processes, (ii) providing a basis for assessing potential improvements in the environmental performance of a product system. However, there are still some weaknesses and limitations associated with LCA. For example, LCA requires large amounts of detailed data, time and expert knowledge necessary to apply it (Herman *et al.*, 2007). To perform LCA studies in a comprehensive manner, the ISO 14040 (1997) has been developed with a four step approach: goal and scope definition, life cycle inventory (LCI) analysis, life cycle impact assessment (LCIA), and interpretation of results (Figure 3.1). A brief description of these steps is provided in the following paragraphs.

(1) Goal and scope definition

This phase defines the goal and scope of an LCA. The goal of the study includes a statement of the rationale for conducting the study, the intended application of the results, and the intended audience. The scope of an LCA determines areas such as the function of the product system, the functional unit, allocation procedures, system boundaries, type of impact assessment methods, data requirements/quality, assumptions and limitations, and report format and need for critical review. Further guidance regarding other aspects of goal and scope definition are found in ISO standards 14040 and 14044 (ISO, 2006a; 2006b).

(2) Life cycle inventory (LCI) analysis:

The second step is the most work intensive and time consuming of all other phases of an LCA, largely attributed to data collection. LCI involves creating an inventory of flows from and to nature for a product system. Inventory flows include inputs of water, energy and raw materials, and releases to air, water and land. The input and output data required for the construction of the inventory are collected for all activities within the boundary. The data must be related to the function unit defined in the goal and scope definition. The results of the inventory is an LCI that provides information about all inputs and outputs in the form of elementary flow to and from the environment from all the unit processes involved in the study.

(3) Life cycle impact assessment (LCIA)

The third phase of LCA aims to understand and evaluate the significance of the potential environmental impacts based on the LCI flow results, which comprises three mandatory elements (steps): selection of impact categories, category indicators and characterization models; assignment of LCI results (classification); and modelling of category of indicators (characterization). Classification is the process of assignment and initial aggregation of LCI data into common impact groups, for example, CO_2 is assigned to global warming. Characterization is the conversion of LCI results to common values within each impact category so that results can be aggregated into category indicator results. Characterization factors are commonly referred to as equivalency factors. The ISO 14040 also suggests optional elements that can be included in an LCA: normalization, weighting and grouping. Normalization expresses potential impacts in ways that can be compared. Valuation assesses the relative importance of environmental burdens identified in the classification, characterization, and normalization stages by assigning them weighting which allows them to be compared or aggregated. Grouping assigns impact categories into one or more groups and sorts them according to geographical relevance and company priorities, and so on.

Several methodologies exist for the calculation of the environmental impact of a product. These include, among others, the Eco-Indicator 99 (Goedkoop, 2002), Recipe 2008 (Goedkoop *et al.*, 2009), USES-LCA (Huibregts *et al.*, 2000), LIME (Itsubo & Inaba, 2003), IMPACT 2002+ (Jolliet *et al.*, 2003), EDIP 2003 (Hauschild & Potting, 2005), LUCAS (Toffoleto *et al.*, 2007), CML 2002 (Guinee, 2002), Carbon Footprint (Commission, 2007), and so on. These methodologies evaluate the environmental impact using so-called impact categories such as climate change or global warming, acidification, eutrophication, stratospheric ozone depletion, photo oxidant formation, resource use, land use, and others.

(4) Interpretation of results

The primary aim of an LCA is to draw conclusions that can support a decision or can provide a readily understandable result of an LCA. Results of either the inventory analysis (LCI) or the impact assessment (LCIA), or both, are evaluated in relation to the goal and scope of the study in order to reach conclusions and recommendations. This is a systematic technique to identify and quantify, check and evaluate information from the results of the LCI and LCIA, and communicate them effectively. According to the ISO:14040 (2006), the interpretation of the LCA or an LCI comprises three main elements: (i) identification of significant issues based on the results of the LCI and LCIA phases of an LCA, (ii) evaluation of results, considering completeness, sensitivity, and consistency checks; and (iii) conclusions, limitations and recommendations.

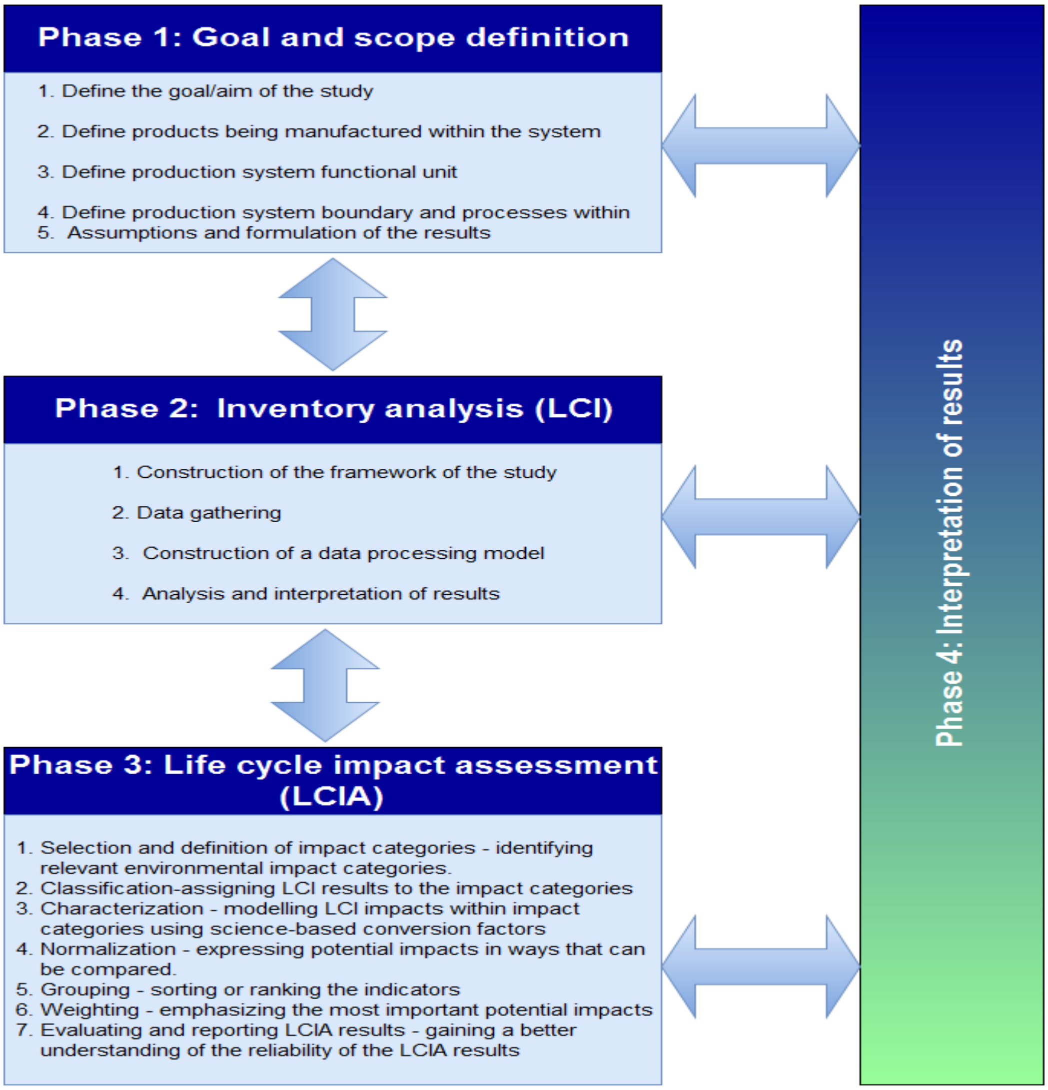

Figure 3.1: Life cycle assessment framework. Source: Adapted from ISO (2006)

3.5.2 Analytical Hierarchy Process

Decisionmaking associated with environmental and social performance of manufacturing companies is complex, multifaceted, and has different stakeholders with priorities and agendas. In addition, it requires a multidisciplinary knowledge base, incorporating natural, physical, and social sciences, politics, legal issues and ethics. In this work, the AHP is adopted to help decision-makers select appropriate sustainability indicators for the Malawian tea industry. The AHP is one of the multicriteria decisionmaking techniques that was developed by (Saaty, 1980, 1990). It is a mathematical decision support tool to analyse complex decision problems with multiple conflicting and subjective criteria while considering tangible and intangible aspects.

AHP is unique because of its inherent capability to consider multiple factors, and to capture perspectives of multiple stakeholders (Shapira & Simcha, 2009). It provides a systematic method for comparing and weighting of these multiple criteria and alternatives by decision-makers. At its core, the AHP technique is based on the principles of decomposition, comparative judgements, and synthesis of priorities. Decomposition structures the problem into objectives, criterions and sub-criterions, and decision alternatives (Akadiri, 2011). Decision-makers elicit pairwise comparisons, based on their value judgments of the elements of the same level with respect to an element on a higher immediate level. Finally, the priorities of alternatives and the criteria for weights are synthesized into an overall rating based on which alternative is decided to be the best. The procedure for solving a problem using AHP is summarized in the following steps (Figure 3.2):

1. Structuring the decision problem

The first step in AHP is to decompose the problem into a hierarchy of criteria and alternatives. AHP starts with an identification of the criteria to be used in evaluating different alternatives, which are organized in a tree-like hierarchy. The hierarchy is built from the top (target) through intermediate levels (criteria) to the very lowest level (the list of alternatives). Decision components and elements are usually a combination of both objective and subjective ones, with measurements in different and multiple dimensions.

2. Eliciting judgment in paired comparisons

Pairwise comparisons of elements on the same level, with respect to elements on the immediate upper level, is carried out in the AHP. To achieve a unidimensional scaling property of the comparisons, (Saaty, 1980) established the famous Saaty fundamental 9-point scale as shown in Table 3.1. In pairwise comparisons, a reciprocal characteristic exists. For example, comparing a_1 and a_3 must be rated $1/3$, which is a reciprocal of 3. Priority vector or weights (ω) are obtained from the pair wise comparison matrix (A) by solving an eigenvalue problem using the following relation:

$$A\omega = \lambda_{max}\omega \quad (1)$$

where λ_{max} is the maximum eigenvalue of the positive reciprocal square matrix (A). The approach also provides a way to measure the consistency of judgments in the pairwise comparison matrix. When decision-making in the pairwise comparison matrix is consistent $\lambda_{max} = n$; otherwise, $\lambda_{max} \geq n$ where n is the number of elements being compared. The Consistency Index (CI), as a measure of degree of consistency, is calculated using the formula:

$$CI = \frac{(\lambda_{max} - n)}{(n - 1)} \quad (2)$$

The consistency ratio (CR) is computed as

$$CR = \frac{CI}{RI} \quad (3)$$

where RI is the mean random consistency index. $CR \leq 0.1$ is an acceptable degree of consistency (Saaty, 1980). Otherwise, the subjective judgment should be repeated until the desired CR value is achieved.

Table 3.1: Saaty fundamental scale

Rate	Definition	Explanation
1	Equal importance	Two elements contribute equally to the objective
2	Weak	Between equal and moderate
3	Moderate importance	Experience and judgment slightly favour one element over another
4	Moderate plus	Between moderate and strong
5	Strong importance	Experience and judgment strongly favour one element over another
6	Strong plus	Between strong and very strong
7	Very strong or demonstrated importance	An element is favoured very strongly over another; its dominance demonstrated in practice
8	Very, very strong	Between very strong and extreme
9	Extreme importance	The evidence favouring one element over another is one of the highest possible order of affirmation

Source: (Saaty, 1980)

3. Synthesizing judgments

According to Saaty (1980), synthesizing judgments in AHP is done by weighting the elements being compared on the lower level to an element on the next immediate level, referred to as the parent element, by the priority of that element and summing up all parents for each element on the lower level. This is referred to as the distributive mode of the AHP. This can be represented in the form below:

$$w_j = \sum_{i=1}^{n} c_i x_{ij} \quad (4)$$

where w_j is the global weight of alternative j, c_i is the weight of criteria i with respect to the goal, and x_{ij} is the local weight of alternative j with respect to i. Alternatively, in matrix form

$$W^T = XC^T \quad (5)$$

where W is an mx1 matrix, X is an mxn $(j \in m, i \in n)$ matrix of alternative weights with respect to each criterion and C is a 1xn matrix of criteria weights. This synthesized vector of priority weights of alternatives is also termed as the global priority vector.

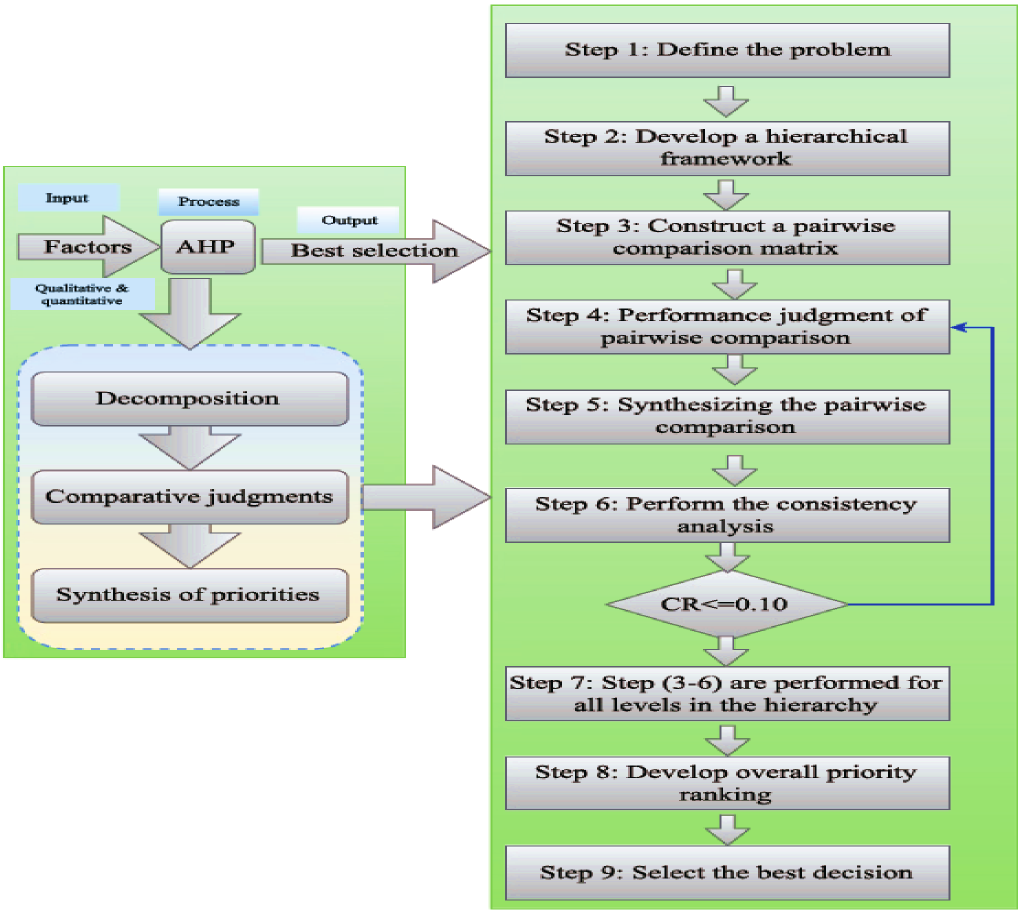

Figure 3.2: Analytic hierarchy process steps

3.6 Sustainability indicators and metrics

Sustainability indicators are becoming increasingly important as tools for examining sustainable performance of manufacturing firms. Sustainability indicators[1] or metrics[2] have been used as quantitative measures of sustainability performance. According to Schwartz *et al.* (2002), "sustainability metrics and indicators support decision-makers in setting goals, gauging a company's progress, benchmarking, and comparing business and technology alternatives in terms of sustainability." Although the specific sets of measurements vary among companies, it is increasingly accepted that these indicators and metrics should cover the three basics of sustainability: social, economic, and environmental concerns.

Criteria for selecting these indicators and metrics have been proposed by several authors. According to (Staniskis & Arbaciauskas, 2009b), for example, selected indicators should address the following aspects: "(i) identify areas where performance improvement options are most feasible; (ii) identify losses, to facilitate development of improvement options; (iii) assess whether objectives and targets have been achieved; (iv) assess legal compliance; (v) assess effectiveness of implemented measures; and (vi) to enable development of sustainability report that meets the requirements of stakeholders". Belton and Stewart (2002) have defined desirable qualities for indicators of sustainable production: (i) value relevance; (ii) understandability; (iii) measurability; (iv) non-redundancy; (v) judgmental independence; (vi) balance of completeness and conciseness; (vii) operationability; and (viii) simplicity versus complexity.

Moreover, sustainability literature is replete with studies on metrics and indicators as well as measurement systems. For comprehensive overview of metrics or indicators for measuring sustainability, readers are referred to studies by (Finnveden & Moberg, 2005; Hák *et al.*, 2007; Herva *et al.*, 2011; Ness *et al.*, 2007; Singh *et al.*, 2009). More recent paper reviews of indicators are given in Roca and Searcy (2012) and Joung *et al.* (2013). However, the majority of indicators focus on measuring sustainability on a global, regional or country level. As stated by (Tuazon *et al.*, 2013), the Global Reporting Initiative is the most extensive and widely subscribed to.

Research on the application of sustainability indicators and metrics is underway, with some researchers targeting specific industry, while others have developed composite indicators in an effort to address a broad set of issues. For example, research has, among others, been conducted for the mining (Azapagic, 2004), manufacturing (Veleva & Ellenbecker, 2011), steel (Singh *et al.*, 2007), aluminium

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[1] Indicator – a summary measure that provides information on the state of, or change in, the system that is being measured. e.g. weight of tea produced per unit of energy delivered.

[2] Metric – the measured value(s) used to assess specific indicators. It defines the units and how the unit is being measured. e.g. kilograms of tea per kilowatt-hour.

(Nordheim & Barraso, 2007), process (Labuschagne *et al.*, 2005) sectors, but surprisingly, the tea industry is not among the industries studied. Krajnc and Glavic (2005) also proposed a general methodology to compare the sustainability performance of different companies. Finally, sustainability indicators could be based on validated and recognized sources of standards and other normative documents as: Global Reporting Initiative (GRI), ISO 9001, ISO 14001, OHSAS 18001, ISO 26000, ISO 14040, Agenda 21, Global Compact, SANS (2008), and so on (Louette, 2008). There are also many third party organizations such as Rain Forest Alliance, Flo-Cert, and UTZ that have created standards, and can certify a company as being sustainable based on specific test methods.

3.7 Manufacturing Productivity

The second concept of this chapter is productivity. Manufacturing productivity has become an intensely researched topic, and received significant academic attention over the last several decades. Moreover, it is widely acknowledged that productivity is one of the managerial attributes crucial for enterprise competitiveness and profitability, empirically supported as a key factor for business performance, and a prerequisite for continual improvement (Kaydos, 1991). At the same time, productivity is increasingly becoming a key issue for organizational survival and success in the long term. Furthermore, it is increasingly being used as a benchmark for comparison between companies as well as a measure by management to gauge the current and future effectiveness of a company. Additionally, productivity has economic, social and environmental dimensions. There is considerable literature on manufacturing productivity. Kendrick (1984), (Solow, 1957), (Sumanth, 1979) and many other authors have contributed to the vast literature on measuring, improving and interpreting productivity growth. Among others, Bartelsman and Doms (2000), Syverson (2011), and Muthiah and Huang (2006) provide a systematic review of studies on productivity within past decades.

Manufacturing productivity is both conceptually and empirically important to industry, especially, the Malawian tea industry. There is no denying that, with the fewer resources this industry uses to manufacture made tea, the more competitive the industry positions itself, *ceteris paribus*. Research evidence suggests that an increase in productivity correlates well with increased profitability (Proverbs *et al.*, 1998), competitiveness (Kendrick, 1984; Singh *et al.*, 2000), and long term growth and sustainability of an organization (Harper, 1984; Sumanth, 1985). It is now an established fact that an increase in productivity will cause a corresponding decrease in production costs; improves quality; and leads to better profitability (Bashir *et al.*, 2014).

In addition, plenty of evidence suggests that higher productivity implies lower operating costs, which in turn leads to competitive advantage and increased profitability. Conversely, below par and growth rates in productivity threatens the survival of an organization. On the other hand, a decline in productivity will result in an increase in costs and therefore deterioration in the competitive position of the firm. Thus, higher-or-lower-productivity affects costs, prices, profits, output and investment and plays a part in growth of industries.

Moreover, changes in productivity are of great importance at all levels – national, industrial, companies, and personal (Kendrick, 1993). More improved measures of productivity to the manufacturing industry positively influences profitability, reduces costs and product prices, which in turn strengthens its competitiveness in the international market. According to prevailing thinking, improvements in productivity leads to additional savings and better utilization of resources, which could further improve productivity in future periods. More improved measures of productivity result in better remuneration and working conditions to the employees as well as better returns to investors. Most important, productivity improvement directly results in improvement of people's living standards. This is measured as per capita income, which, to a greater extent, depends on the ability of a country's firms to attain high levels of productivity (Porter, 1990). With the aim to maintain their competitiveness, manufacturing companies need to embrace the notion of productivity, with a view to sustain long term growth and profitability. They also need to focus on increasing productivity and embrace productivity as an integral part of their businesses. However, there is a lack of understanding of the notion of productivity, its measurement and interpretation. For detailed discussion about the concept of productivity, productivity measurement models, linkages between productivity and social and environmental sustainability, interested readers are referred to Appendix B of this dissertation.

3.8 Chapter summary

The aim of this chapter was to present a review on state-of-the-art on two broad concepts of sustainability and productivity. Drivers and benefits as well as tools and methods for measuring sustainability have been presented and discussed. The chapter has highlighted the importance of integrating sustainability with manufacturing, along with the need to integrate LCA and AHP. The chapter also provided an overview of concepts, approaches and models for measuring productivity of firms. Furthermore, the literature review has described the linkage between productivity and the environmental and social dimensions of sustainability.

Several messages or themes have emerged from this review. (1) Both sustainability and productivity as concepts are complex, heavily contested notions, with several dimensions. No universally accepted definition or assessment techniques of sustainability and productivity exist. These concepts cover a complex range of ideas and meanings. While there are varying definitions of sustainability from different sectors of the industry, what is more important is that it strives for the protection of the environment, prudent use of natural resources, equitable social progress, and maintenance of economic well-being without compromising the environment and society. (2) The measurement of both sustainability and productivity is fraught with problems and methodologies, and different models chosen can greatly influence those estimates. (3) A comprehensive management framework to address balance and integrates triple bottom-line considerations is also absent. (4) The review revealed that achieving sustainability in industry would require tailor-made frameworks and models, indicators and metrics for sustainability evaluation.

The key challenge to researchers is to provide methodologies and tools that are simple and could meaningfully be understood and used by the manufacturing industry. The following chapter reviews the extant literature on multi-objective optimization.

Chapter-4
Multi-objective optimization

4.1 Introduction

This chapter reviews the literature on multi-objective optimization, which forms the central topic of this study. The chapter is divided into nine sections. The first section presents examples of decision-making problems that make use of multi-objective optimization techniques particularly attractive for managing tea production processes. The second section provides a brief background of multi-objective optimization. The third section summarizes the basic principles of multi-objective optimization and introduces the principles of dominance and Pareto optimality. The fourth and fifth sections briefly describe different methods including classical methods and evolutionary algorithms for solving multi-objective optimization problems. The sixth section focuses on the basic concepts, features and working flow of genetic algorithms. The seventh section explores three important issues that have to be considered in multi-objective genetic algorithms. The eighth section contains a brief description of state-of-the-art multi-objective evolutionary algorithms. The final section summarises the chapter.

4.2 Multi-objective optimization problems

Decision-making processes in the tea industry are complex in nature and involve many different approaches, parameters, and several incommensurable and often conflicting objectives. Tea cultivation and manufacturing is a decision-making process that aims to maximize profits while reducing operating costs. Decision-makers in this industry strive to minimize the operational costs of their business while maintaining a stable work force. Environmental impacts as well as the social well-being of employees and other stakeholders are also two important, but conflicting objectives to be considered simultaneously. These kinds of problems are generally known as multi-objective optimization (Ehrgott, 2005). Solving these complex decision problems requires the use of mathematical techniques that are formulated to take simultaneous consideration of conflicting objectives (Adeyemo & Otieno, 2009). In this chapter, the author argues that the challenges being experienced in the tea industry should incorporate a multi-objective optimization approach to simultaneously optimize the conflicting objectives. Such an approach will provide multiple solutions characterising trade-offs between objectives.

Traditional approaches to solving multi-objective optimization problems ordinarily involve combining them into a single objective function composed of their weighted sum, or by focusing on a single objective while transforming the other into constraints (Chankong & Haimes, 1983). However, this approach suffers from several setbacks. Firstly, it requires a priori knowledge about the relative importance of the objectives, and the limits on the objectives that are converted into constraints. Nevertheless, conversion of multiple objectives into a single objective necessitates scaling of objectives to ensure that all objectives are comparable. Secondly, these optimization techniques provide only one optimal solution even if other possible solutions exist. Thus, a thorough exploration of the trade-off between different objectives requires many optimization runs to be carried out. Thirdly, trade-offs between objectives cannot be easily evaluated. Fourthly, the solution may not be attainable unless the search space is convex. To overcome these drawbacks, multi-objective optimization using a Pareto dominance approach can be implemented. This approach is explained in detail in the following sections.

4.3 Multi-objective optimization and Pareto optimal solutions

Marler and Arora (2009) defined multi-objective optimization (MOO) "as an approach that involves the simultaneous optimization of several competing objectives while finding an optimum solution over a set of decisions. Multi-objective optimization problems (MOOPs) with conflicting objectives do not have a single optimum solution, but a set of them, called '*Pareto optimum*', non-dominated, efficient, non-inferior, or *Pareto optimal solutions* (Chankong & Haimes, 1983; Fonseca & Fleming, 1998; Miettnen, 1999), which correspond to the best possible trade-offs among the objectives. These solutions are contained in the so-called *Pareto optimal set* while their corresponding objective function values are called the *Pareto front*. The most common method is to choose the best trade-offs among all defined objectives that are in conflict with each other. Therefore, multi-objective optimization algorithms aim to find Pareto optimal solutions. For an introduction to the concepts of multi-objective optimization as well as a review about the Pareto set generation readers are referred to books by (Chankong & Haimes, 1983; Coello Coello, 1999; Deb, 2001; Ehrgott, 2005; Hwang & Masud, 1979; Miettnen, 1999; Sawaragi *et al.*, 1985; Steuer, 1986). Furthermore, survey papers with a focus on solution methods can be found in Hillermeier and Jahn (2005), and (Ruzika & Wiecek, 2005).

Multi-objective optimization is also one of the most heavily researched subjects that has been studied for more than a century. Edgeworth proposed a scalarization technique called a utility function for multi-objective optimization as early as 1881. Pareto (1906) introduced the concept of Pareto optimal solutions in 1906. Kuhn and Tucker (1951) formulated optimality conditions for multi-objective optimization. The first implementation of multi-objective evolutionary algorithm was suggested by Schaffer (1985), while Goldberg (1989) suggested a new non-dominated sorting procedure using the concept of domination to give preference to non-dominated individuals in the population. Since then, research interests in this field have remained strong and a variety of MOO techniques has been developed. Rangaiah (2008) states that "the increasing application of multi-objective optimization in industry is due to the availability of new and effective methods for solving multi-objective problems as well as increased computational resources". This study adopts the multi-objective optimization techniques to solve some problems facing the Malawian tea industry for the following reasons: (i) they are capable of simultaneously handling several and often conflicting objectives; (ii) they have a global perspective and are not affected by multiple global or local optima, do not require information about function derivatives, and can be applied to functions that are non-convex, non-concave and discontinuous; and (ii) they have the ability to generate multiple solutions that span the entire search space. In the next section, the basic concepts for multi-objective optimization are briefly described.

4.4 Basic concepts and notation

Multi-objective optimization involves simultaneously optimizing a set of two or more objective functions. This section presents the fundamental concepts of multi-objective optimization. For more detailed information, interested readers are referred to (Steuer, 1986).

4.4.1 Definitions

Osyczka (1985) defines multi-objective optimization as the problem of finding:

> "a vector of decision variables which satisfies constraints and optimizes a vector function whose elements represent the objective functions. These functions form a mathematical description of performance criteria, which are usually in conflict with each other. Hence, the term 'optimize'' means finding a solution which would give the values of all objective functions acceptable to the decision maker "(Osyczka, 1985).

Marler & Arora (2009) describe multi-objective optimization as "the process of optimizing systematically and simultaneously a collection of objective functions".

4.4.2 Multi-objective optimization problem formulation

This sub-section presents the formulation of a typical multi-objective optimization. Fonseca and Fleming (1995) provide a formal notion of multi-objective optimization. Conceptually, a general multi-objective optimization problem includes a set of *n* decision variables (parameters), a set of *m* objective functions, and a set of *k* constraints. Objective functions and constraints are functions of the decision variables. Without loss of generality, a multi-objective optimization problem can be represented as follows (Deb, 2001):

$$\text{Minimize } \boldsymbol{f}(\vec{x}) = \{f_1(\vec{x}),\ f_2(\vec{x}), \dots, f_m(\vec{x})\} \qquad m = 1, 2, \dots, n \qquad (6)$$

subject to the q inequality constraints:

$$g_i(\vec{x}) \le 0 \qquad i = 1, 2, \dots, \quad q \qquad (7)$$

and the p equality constraints:

$$h_j(\vec{x}) = 0 \qquad j = 1, 2, \dots, \quad p \qquad (8)$$

and l decision variable bounds

$$\vec{x}_{k\ lower} \le \vec{x}_k \le \vec{x}_{k\ upper} \qquad k = 1,2, \dots, \quad l \qquad (9)$$

where: $f(\vec{x})$ consists of m (≥ 2) objective functions $f_{i:}$ $\mathbb{R}^n \to \mathbb{R}:, i = 1, 2, \ldots\ldots, m$; $\mathbb{R}^n$ is the objective space that we want to minimize simultaneously. $\vec{x} = [\vec{x}_1, \vec{x}_2, \ldots.., \vec{x}_n]^T$ is the vector of decision variables that is mapped in the decision (search) space; f_m, $m = 1, 2, \ldots, n$ are the objective (also known as fitness or cost) functions; g_i $i = 1,2, \ldots.., q$ denotes the mathematical inequality constraint functions in the decision space; $h_j(\vec{x})$ $j = 1,2, \ldots.., p$ denotes the mathematical equality constraint functions in the decision space; $\vec{x}_{k\ lower} \leq \vec{x}_k \leq \vec{x}_{k\ upper}$ $k = 1,2, \ldots..,$ l are called decision variable bounds that restrict each decision to be within the lower and upper bounds; n is the number of objective functions; q is the number of inequality constraints; p is the number of equality constraints; l is the number of decision variables; $\vec{x}_{k\ lower}$ is the lower bound for decision variable $\vec{x}_k$; $\vec{x}_{k\ upper}$ is the upper bound for decision variable $\vec{x}_k$.

A solution $\vec{x} \in \mathbb{R}^n$ is a vector of *n* decision variables: $\vec{x} = [\vec{x}_1, \vec{x}_2, \ldots.., \vec{x}_n]^T$ and the objective function vector for a solution $\vec{x}$ is $f(\vec{x}) = [f_1(\vec{x}), f_2(\vec{x}), \ldots.., f_m(\vec{x})]^T$. The solutions satisfying the constraints and variable bounds constitute a feasible decision variable space $S \subset \mathbb{R}^n$. Without loss of generality in the rest of this dissertation, it is assumed that all objectives are of the minimization type – a minimization type objective can be converted to a maximization type by multiplying negative one (Snyman, 2005).

4.4.3 Pareto optimality

The concept of Pareto optimality or non-dominance is arguably the basis for multi-objective optimization. Perhaps it is worthwhile to note that the notions of Pareto dominance and Pareto optimality were originally proposed by Francis Ysidro Edgeworth in 1881, and then generalized by Vilfredo Pareto in 1896 (Pareto, 1906). A point x^* in the feasible design space S is *Pareto optimal* if and only if another point x does not exist in the set S such that $f(\vec{x}) \leq f(x^*)$ with at least one $f_i(\vec{x}) < f_i(x^*)$. In other words, a solution belongs to the Pareto set if there is no other solution that can improve at least one of the objectives without degradation of any other objective. For a given Pareto optimal set, the corresponding values of objective functions in the objective space comprise the Pareto front. Deb (2001) correctly points out that a solution $x^* \epsilon\, X$ is said to be dominated by $\vec{x}\, \epsilon X$, if both the following two conditions are satisfied:

(1) The solution $\vec{x}\, \epsilon X$ is not worse than $x^* \epsilon\, X$ in all objectives; and

(2) The solution $\vec{x}\, \epsilon X$ is strictly better than $x^* \epsilon\, X$ in at least one objective. If any of the above two conditions are violated, $x^* \epsilon\, X$ is known to be non-dominated by $\vec{x}\, \epsilon X$ or non-inferior to. The domination between two solutions is defined as follows:

Definition 1: Pareto Dominance

In the context of multi-objective optimization, a decision vector $\vec{x}_1 \in X$ is said to *strictly dominate, or dominate* a decision vector $\vec{x}_2 \in X$ (denoted by $\vec{x}_1 \preccurlyeq \vec{x}_2$) if it is better than or equal to $\vec{x}_2$ on each objective function, and better in at least one of the objectives. More formally, $\vec{x}_1$ dominates $\vec{x}_2$ (denoted by $\vec{x}_1 \preccurlyeq \vec{x}_2$) *if and only if* $f_1(\vec{x}\,)$ is partially less than $f_2(\vec{x}\,)$ such as:

$$\forall i \in \{1, 2, ., k\} \quad f_i(\vec{x}_1) \leq f_i(\vec{x}_2) \quad \wedge \exists i \in \{1,2, ., k\} \qquad f_i(\vec{x}_1) < f_i(\vec{x}_2) \qquad (10)$$

A decision vector $\vec{x}_1 \in X$ is said to weakly dominate a decision vector $\vec{x}_2 \in X$ (denoted by $\vec{x}_1 \preccurlyeq \vec{x}_2$) if it is not worse than $\vec{x}_2$ on each objective function. More formally, $\vec{x}_1$ dominates $\vec{x}_2$ *if and only if* (iff):

$$\forall i \in \{1, 2, ., k\} \quad f_i(\vec{x}_1) \leq f_i(\vec{x}_2) \qquad (11)$$

Based on the dominance notion, it can be said that $\vec{x}_1$ is preferable to $\vec{x}_2$ when solution $\vec{x}_1$ dominates solution $\vec{x}_2$. The concept of Pareto dominance is illustrated in Figure 4-1 in which the underlying optimization problem is to minimize two objective functions. In this figure, solutions 1 and 2 are non-dominated and 3, 4, 5 and 6 are dominated solutions

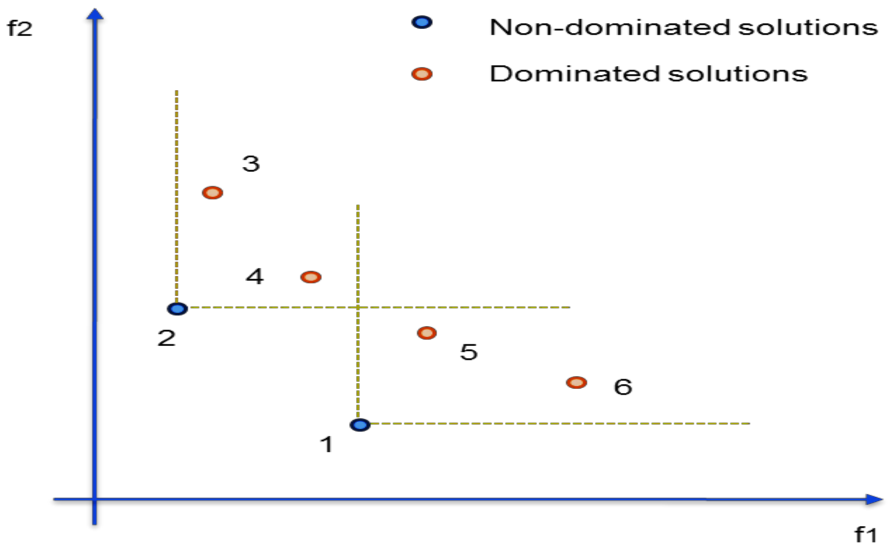

Figure 4.1: Dominance relation in solution space for a two-objective problem

Definition 2: Pareto Optimality

A feasible solution $x^* \in F$ (where F denotes the feasible region of the problem) *is Pareto optimal, if and only if* there is no feasible solution $x_b \in F$ such that $x_b \preccurlyeq x^*$. According to this definition, x^* is referred to as *Pareto optimal, if and only if* there does not exist any other feasible solution x_b that would improve some objectives without causing a simultaneous degradation in at least one other objective. Therefore, the solution to a multi-objective optimization problem (MOOP) considering Pareto optimality is a set of feasible, non-dominated solutions that is referred to as the *Pareto optimal set*.

Definition 3: Pareto Optimal Set

The Pareto set is a set of solutions or decision vectors that are minimal. The Pareto optimal set, P^*, can be defined as:

$$P^* = \{x^* \in F \mid \nexists\, x \in F, \quad x \preccurlyeq x^*\} \tag{12}$$

A solution $x^* \epsilon X$ is a Pareto optimal solution or a non-dominated solution, if and only if another solution $x \epsilon X$, $f(x) \prec_{pareto} f(x^*)$ does not exist. When the solutions in the *Pareto optimal* set are plotted in the objective space, they are collectively called a *Pareto front.*

Definition 4: Pareto Front

Pareto front is the set of objective vectors of the Pareto set. Thus, for a set of Pareto optimal solutions (P^*), the Pareto front (PF^*) is defined as:

$$PF^* := \{\, \boldsymbol{f}(x) = (f_1(x), f_2(x), \ldots\ldots, f_n(x) \mid x \in P^*)\} \tag{13}$$

Each solution has a point on the Pareto front and represents a vector whose components are the trade-offs in the decision space. However, since the Pareto front can contain a large number of points, a good solution is to find a limited number of these points, which should be uniformly spread over the Pareto front and also be found as close as it can be to it. Also choosing a solution over another is undoubtedly a matter of user decision.

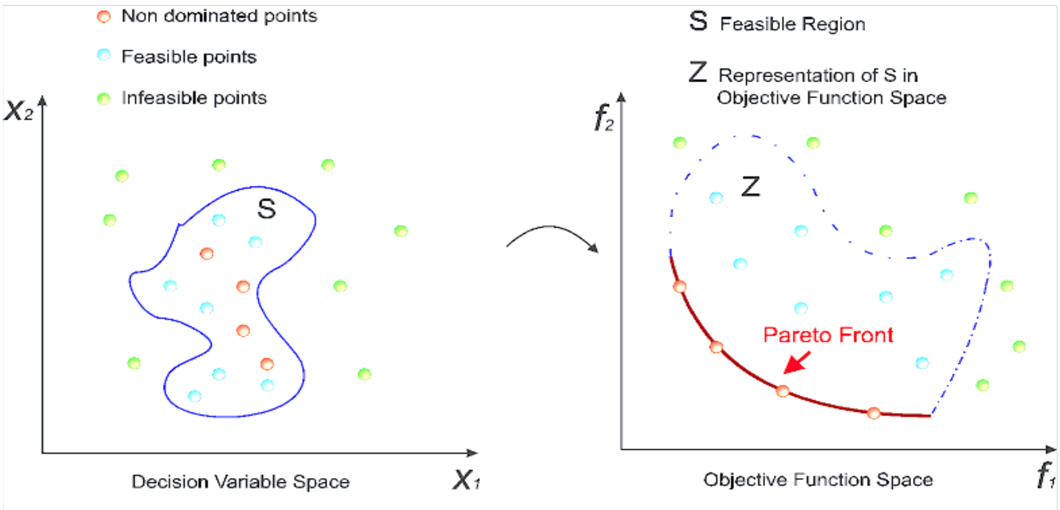

Figure 4.2: Pareto optimal front for a bi-objective problem

Definition 5: Pareto Ranking

An individual's rank corresponds to the number of individuals in the current population in which it dominates. One of the simplest methods for computing fitness values is to let the individuals directly reflect the Pareto dominance relation. Figure 4.1 illustrates the Pareto dominance relations in a population of six individuals for minimizing a bi-objective problem.

Definition 6: Global and Local Pareto Optimal Sets

Like global and local optimal solutions in the single-objective optimization, there will be global and local Pareto optimal sets in multi-objective optimization (MOOP). Therefore, in the MOOP case, the concept of a globally optimal solution infers that an improvement in one objective results in deterioration in another. Similarly, local optima may exist when a non-dominated set within a neighbourhood is obtained.

Let $\acute{X} \in X$ be a set of decision vectors

i. The set $\acute{X}$ is denoted as a *local Pareto optimal set if and only if*

$$\forall \acute{a} \in X : \acute{a} \prec \acute{a} \wedge \quad \| a - \acute{a} \| < \varepsilon \wedge \| f(a) - f(\acute{a}) \| < \delta \tag{14}$$

where$\|.\|$ is the corresponding distance metric and $\varepsilon > 0,\ \delta > 0$.

ii. The set $\acute{X}$ is denoted as a *global Pareto optimal set if and only if*

$$\nexists\, \acute{a} \in X : \nexists\, a \in X : a \prec \acute{a} \tag{15}$$

4.4.4 Classification of methods in multi-objective optimization

This section reviews the preference-based methods for multi-objective optimization. Horn (1997) has identified two conceptually distinct types of problem difficulty in solving a multi-objective optimization problem: search and decision-making. The first aspect refers to the optimization process in which the feasible set is sampled for Pareto optimal solutions. The second aspect is concerned with the problem of selecting a suitable compromise solution from the Pareto optimal set. In this process, the decision maker (DM) has to apply his preferences among the objectives to select the final solution. Following a classification by van Veldhuizen and Lamont (1999) and Hwang and Masud (1979), the articulation of preferences may be done either before (a priori), during (progressive/interactive), or after (posteriori) the optimization process.

- **Priori Preference Articulation**: The decision maker articulates preferences before optimization. The DM gives preference information to the analyst before solving the problem. This preference information may be given in two ways, the DM will give some judgment about specific objective preference levels or he will rank the objectives in order of their importance (Hwang and Masud (1979). Utility functions, lexicographic ordering, goal programming and fuzzy logic are typical examples of priori preference articulation;

- **Posteriori Preference Articulation:** The analyst presents the subset of complete set of non-dominated solutions to the DM, who then implicitly uses the trade-off information in order to select the preferred solution. Typical examples of this method include the weighted sum, ε-constraint method, genetic algorithms, evolutionary algorithms, and simulated annealing (Hwang and Masud (1979).

- **Progressive Preference Articulation**: Decision maker interacts with the optimization program during the optimization process. At each iteration of the solution, preference information is expected from the DM. The DM may not provide any priori information in this case, but gives the preference information on a local level to a particular solution (s) presented. After the limited number of interactions with the DM, these methods lead him to the final or preferred solution.

Figure 4.3 presents the classification of multi-objective optimization methods.

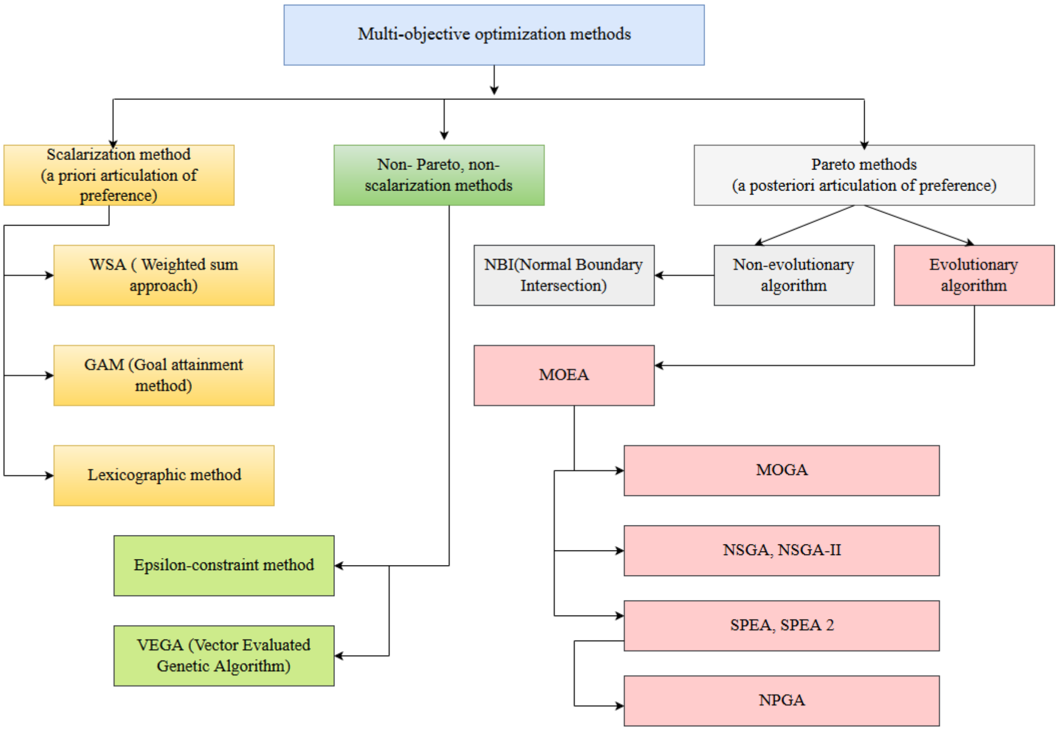

Figure 4.3: Classification of multi-objective optimization methods. *Source*: Samari & Habiba (2013)

4.5 Classical optimization methods

Several approaches for solving multi-objective optimization problems have been reported in the literature (Coello Coello, 1999; Srinivas & Deb, 1994). Typical algorithms for solving multi-objective optimization problems include the weighted sum (Cohon, 1985), the ε-constraint (Chankong & Haimes, 1983), goal attainment (Fonseca & Fleming, 1998), goal programming , distance based method and direction based method. These are briefly discussed in the following subsections.

4.5.1 Weighted Sum Method

Proposed by Ishibuchi and Murata in 1996 (Ishibuchi & Murata, 1996) the weighted sum method (WSM) is probably the simplest and the most widely used classical approach. The WSM converts the multi-objective optimization problem into a scalar problem by constructing a weighted sum of all objectives. The decision maker defines and assigns weighting coefficient w_i for each objective and then adds them together to transform them into an aggregated objective. Eq. (16) can be used to represent the weighted sum method:

$$\text{minimize } f(x) = w_1.f_1(x) + w_2.f_2(x) + \cdots, +w_k.f_k(x) \quad (16)$$

$$\text{subject to } x \in X_f$$

where $w_i \geq 0$ for all $i = 1, \ldots, k$ are the weighting coefficients representing the relative importance of the *m* objective functions of the problem. The above equation can be written as follows:

$$\text{minimize } Z = \sum_{i=1}^{k} w_i f_i(x)\text{, with } 0 \leq w_i \leq 1\text{, and } \sum_{i=1}^{k} w_i = 1 \quad (17)$$

$$\text{subject to } x \in S$$

where the weights are non-negative, that is $w_i \geq 0$ for all $i = 1, \ldots, k$. Without loss of generality the following normalization of the weighting coefficients is employed.

$$\sum_{i=1}^{k} w_i = 1 \quad (18)$$

The WSM has the inherent advantage of being simple for implementation and efficiency in computation. For problems having a convex Pareto-optimal front, this method guarantees finding solutions on the entire Pareto-optimal set. However, the well-known drawback of this approach is that it cannot generate all Pareto optimal solutions with non-convex trade-off surfaces (Deb, 2001; Diwekar, 2003). In addition, it is difficult to control diversity along the Pareto front (Coello Coello, 1999). Furthermore, the optimization result is highly sensitive to the user-defined weighting coefficient. Another problem with this method is its subjectivity, because the DM needs to provide the weights. Therefore, the weighted sum method is not chosen for this study to address the tea industry's decision-making problems. More information on this method can be found in standard textbooks (Chankong & Haimes, 1983; Ehrgott, 2005; Miettnen, 1999).

4.5.2 Goal programming

Charnes and Cooper (1961) developed the goal programming (GP) method for a linear model, which has gained much popularity for solving multi-objective optimization problems. The GP method is based on the intuitive concept of goal setting. The DM assigns a goal or target to each objective and then seeks to minimize the deviations from each goal. The DM to reflect their relative importance then weights these deviations, which represents both over and under achievement of goals. The GP can be formulated as follows (Duckstein, 1984).

$$min \sum_{i=1}^{k} |f_i(x) - T_i|, \qquad subject\ to\ x \in \Omega \tag{19}$$

where T_i is the target or goal set by the decision maker for the ith objective function $f_i(x)$, and Ω represents the feasible region. The criterion, then, is to minimize the sum of the absolute values of the differences between target values and actually achieved values. Equation (19) can be transformed into linear form by introducing new variables d_i^+ and d_i^- such that(Charnes & Cooper, 1961):

$$d_i^+ = \frac{1}{2}\{|f_i(x) - T_i| + [f_i(x) - T_i]\} \tag{20}$$

$$d_i^- = \frac{1}{2}\{|f_i(x) - T_i| - [f_i(x) - T_i]\} \tag{21}$$

By adding and subtracting these equations, the following equivalent linear formulation may be found:

$$\min z_0 = \sum_{i=1}^{k} (d_i^+ + d_i^-) \tag{22}$$

$$\text{subject to } x \epsilon \Omega \tag{23}$$

$$f_i(x) - d_i^+ + d_i^- = T_i \tag{24}$$

$$d_i^+, d_i^- \geq 0, i = 1, \dots, k \tag{25}$$

The GP method is flexible in dealing with cases that have multiple goals and often conflicting. Moreover, it is simple and computationally efficient. However, the main weakness of the goal programming method is the need for a priori information. The method requires the DM to possess enough priori knowledge to determine the goal for each objective, which is very difficult. As a result, the goal-programming method was considered unsuitable for the present study. More information on this method can be found in Charnes *et al.* (1969), Jones and Tamiz (2002), Lee (1972), and Lee (1971).

4.5.3 ε-constraint method

Haimes *et al.* (1971) proposed the $\boldsymbol{\varepsilon}$-constraint method in order to alleviate the difficulties faced by the weighted sum in solving problems exhibiting a non-convex objective space. The $\boldsymbol{\varepsilon}$-constraint method is one of the best-known scalarization techniques to solve MOOPs. In this approach, one of the objectives is minimized while the others are used as constraints bound by some allowable range ε_i . The MOO problem is iteratively solved for different values of ε_i to generate the entire Pareto set (Coello Coello, 1999). According to (Coello Coello, 1999), the $\boldsymbol{\varepsilon}$-constraint method is formulated as follows:

$$\text{Minimize } f_\mu(x), \tag{26}$$

$$\text{Subject to } f_m(x) \le \varepsilon_m, \quad m = 1,2,\ldots, M \text{ and } m \ne \mu \tag{27}$$

$$g_j(x) \le 0 \quad j = 1,2,\ldots, J \tag{28}$$

$$h_k(x) = 0 \quad k = 1,2,\ldots, K \tag{29}$$

$$x_i^{(L)} \le x_i \le x_i^{(U)} \quad i = 1,2,\ldots, n \tag{30}$$

where the parameter ε_m denotes an upper bound of the value of f_m. Repeat (1) for different values of ε_i.

The $\boldsymbol{\varepsilon}$-constraint method has the advantage of being able to identify different Pareto optimal solutions by varying the value of ε constraints. In addition, the method is capable of solving problems having convex or non-convex objective space. However, this method also has weak points, which are: (i) large dependence on the values of the ε constraints, which are specified by the decision-maker, and the value must be within the minimum and maximum values of the individual objective function; (ii) the decision-maker has to choose appropriate upper bounds for the ε_i values. Moreover, the method is not particularly efficient if the number of objective functions increase. Additionally, since each assignment of ε constraint values searches only one Pareto optimal solution, finding the required number of Pareto optimal solutions may need a large number of iterations and this may be time consuming. Based on the above limitations, the method was found inappropriate for the present study. For a discussion of this method, see Chankong and Haimes (1983), Ehrgott (2005), Haimes *et al.* (1971), Miettnen (1999), and Steuer (1986).

4.6 Genetic algorithms

This section contains a brief description of the fundamental concepts of genetic algorithms. For more details about genetic algorithms and characteristics of different multi-objective genetic algorithms, interested readers are directed to (Coello, 2000; Fonseca & Fleming, 1993; Holland, 1975; Horn, 1997).

4.6.1 Basic concepts of genetic algorithms

Genetic algorithms (GAs) are arguably one of the most successful and widely used multi-objective evolutionary algorithms. The basic principles of genetic algorithms (GAs) were first conceived and developed by Holland (1975) and are well described in many textbooks (Davis, 1991; Goldberg, 1989; Michalewicz, 1994) and reports (Beasley *et al.*, 1993a, 1993b; Srinivas & Patnaik, 1994). GA is a stochastic and adaptive heuristic search algorithm, which is based on the evolutionary principles of natural selection and genetics (Goldberg, 1989; Holland, 1975). GAs are inspired by Charles Darwin's theory of natural selection and survival of the fittest (Cantu-Paz, 2001; Chamber, 1995; Haupt & Haupt, 2004). The theory of natural selection proposes that in nature, competition among individuals for scanty resources results in the fittest individuals dominating over the weaker ones. Consequently, the individuals who best adapt to the environment are the ones who will most likely survive.

Genetic algorithms use an iterative process of selection, crossover (recombination), mutation and evaluation in order to find the fittest candidate solution (Haupt & Haupt, 2004). In addition, GAs operate on a population (a group of individuals) of potential solutions applying the principle of the survival of the fittest to produce successively better approximations to a solution. At each generation, a new set of approximations is created by the process of selecting individuals according to their level of fitness in the problem domain and reproducing those using genetic operators such as selection, crossover and mutation. In other words, at each step, the genetic algorithm randomly selects individuals from the current population and uses them as parents to produce children for the next generation. The fitness function evaluates the quality of solutions coded by strings. Selection allows strings with higher fitness to appear with higher probability in the next generation. Crossover combines two parents by exchanging their parts of strings, starting from a randomly chosen crossover point. Mutation flips the value at a particular location in a string with a very low probability. This process leads to the evolution of better populations than the previous populations. The algorithm terminates when a maximum number of generations has been produced, a satisfactory fitness level has been reached for the population. For a detailed description of genetic algorithms, the reader may refer to Goldberg (1989). More advanced literature is given in Holland (1975).

4.6.2 Features of genetic search

Genetic algorithms are becoming a well-accepted technique for solving multi-objective optimization problems due to their capability of evolving multiple solutions simultaneously approaching the non-dominated Pareto front in a single simulation run, which is an unrivalled advantage over classical methods. GAs are more powerful in difficult environments where the space is usually large, discontinuous, complex and poorly understood. Further, GAs are not guaranteed to find the global optimum solution to a problem, but they are generally good at finding acceptably good solutions to problems rather quickly. Moreover, genetic algorithm can prevent the search from settling in local optima; and do not require computing gradients of the objective function. Importantly, shape and continuity of Pareto front, no matter convex or non-convex, continuous or discontinuous, do not affect the proficiency and efficiency of genetic algorithm (Coello Coello, 1999).

Genetic algorithms have been successfully applied to various optimization problems in science and engineering ranging from gas pipeline design, analogue circuit design, finger-print recognition, and design optimization (Deb, 2001). Major reasons for this success include, but are not limited to the following: (1) they are able to solve complicated problems quickly and reliably; (2) they are easy to interface to existing simulations and models; (3) they are extensible, and are easy to hybridize. To sum up, genetic algorithms are efficient, adaptive and robust. Notably, GAs differ from traditional search/optimization methods in that they:(a) search a population of points parallel, not only a single point, (b) use probabilistic transition rules, not deterministic ones; (c) work on an encoding of the design variable set rather than on the variables themselves; (d) do not require derivative information or other auxiliary knowledge – only the objective function and corresponding fitness levels influence search. However, genetic algorithms have the following disadvantages: (i) they do not work for large problems due to stochastic algorithm, (ii) their convergence depend on problem specific parameters that are not clearly defined; and (iii) they suffer from convergence and computational requirements.

4.6.3 Basic principle of genetic algorithms

In this section, we describe the basic principle of genetic algorithm. We describe the algorithm in three main steps: chromosome representation, selection, genetic operators.

1) Chromosome representation (encoding)

Encoding is the process of representation of individual genes. The process of representation can be performed by using bits, numbers, trees, arrays and list or any other objects (Sivanandam & Deepa, 2008). Several types of encoding schemes have been proposed in the literature. Depending on the structure of encoding, they can be classified 1-dimensional and 2-dimensional. Binary, octal, hexadecimal, permutation and value encodings are 1-dimensional, while tree encoding is 2-dimensional (Gen, 1996). Goldberg (1989) argues that the fitness function for a specific scheme depends on two factors: value and order. According to him, the fitness depends on order only (e.g. permutation); value and order (binary encoding); and value only (e.g. value coding). Most commonly used encoding mechanisms are binary and real encoding. Binary encoding is suitable for problems with discrete and finite decision variables while real encoding is suitable for continuous decision variables.

2) Selection

Selection (or reproduction) is an important part of a genetic algorithm. It is the process of determining the number of times a particular individual is chosen for reproduction and, thus, the number of offspring that an individual will produce. Its purpose is to choose the fitter individuals in the population that will create offspring for the next generation, commonly known as a mating pool. The mating pool thus selected takes part in further genetic operations, advancing the population to the next generation and hopefully close to the optimal solution.

Moreover, selection of individuals in the population is dependent on their fitness function. The higher the fitness function found, the more chance an individual has to be selected (Sivanandam & Deepa, 2008). Furthermore, selection chooses more fit individuals in analogy to Darwin's theory of evolution – the survival of the fittest (Fogel, 1995). Too strong selection would lead to suboptimal highly fit individuals and too weak selection may result in too slow evolution (Mitchell, 1996). Many population selection methods exist in the GA literature. Common techniques used to select parents include tournament selection (Goldberg & Deb, 1991), proportionate selection (Holland, 1975) and ranking selection (Baker, 1985).

Tournament selection (Goldberg, 1989): Tournament selection is increasingly being used as a selection mechanism for genetic algorithms because it is simple to code and efficient for both nonparallel and parallel architecture. In tournament selection, each individual in the population is paired at random (either with or without replacement) with another. The fitness values of each pair are compared. The fitter individual of the pair moves on to the next round, while the other is disqualified. This continues until there are a number of winners equal to the desired number of parents. Then this last group of winners is paired as the parents for new individuals. Tournament selection is known to have better or equivalent performance in terms of convergence and computational time complexity compared with any other selection method that exists in the literature. The tournament selection can be implemented as follows (Deb, 2001):

1. Specify the number of chromosomes in the mating pool, known as mating pool size.
2. Decide tournament size, which is the number of chromosomes in a tournament pool. A commonly adopted tournament size is two.
3. Randomly pick different chromosomes to enter the tournament pool until the number of chromosomes picked is equal to the tournament size.
4. Select the chromosome with the most promising fitness from the tournament to enter the mating pool.
5. Repeat the steps (2) to (4) until the mating pool is fully filled.

Roulette wheel selection (Goldberg, 1989; Holland, 1975): Roulette Wheel Selection (RWS), also known as Fitness Proportionate Selection, is the most common method used in genetic algorithms for selecting potentially useful individuals (solutions) for crossover and mutation. Moreover, it has been extensively used due to its simplicity in implementation. In this method, all the chromosomes (individuals) in the population are placed on the roulette wheel according to their fitness value (Goldberg & Deb, 1991; Goldberg, 1989). Each individual is assigned a segment of the roulette wheel, and the size of each segment is proportional to the individual fitness of chromosomes, that is, the bigger the value is, the larger the size of segment is. Then the virtual roulette wheel is spun. The individuals corresponding to the segment on which the wheel stops are then selected. The process is repeated until the desired number of individuals is selected. It is obvious in roulette wheel selection that individuals with higher fitness have more probability of selection. The disadvantage of this method is that it might lead to biased selection towards high fitness individuals. There is also the possibility of missing the best individuals of a population. Nevertheless, RWS can be implemented as follows:

1. Evaluate the fitness, ω_i, of each individual in the population.

2. Compute the probability (segment size), p_i, of selection of each individual of the population, $p_i = \frac{\omega_i}{\sum_{i=1}^{N} \omega_i}$, where N is the population size.
3. Calculate the cumulative probability, q_i, for each individual, $q_i = \sum_{i=1}^{i} p_j$.
4. Generate a uniform random number, $r\epsilon(0,1)$.
5. If $r < q_1$ then select the first chromosome, x_i such that $q_{i-1} < r \leq q_i$.
6. Repeat steps 4-5 n times to create n candidates in the mating pool.

Ranking selection (Baker, 1985): Ranking selection sorts the population first according to fitness value and ranks them. Each individual in the population is allocated selection probability with respect to its rank (Baker, 1985) and selection is based on this ranking rather than differences in fitness. Ranking selection is an explorative technique of selection. It prevents too quick convergence and differs from roulette wheel selection in terms of selection pressure. Moreover, it overcomes the scaling problems like stagnation or premature convergence. Ranking controls selection pressure by uniform method of scaling across the population. Compared to other methods, Ranking selection is known to behave in a more robust manner (Back & Hoffmeister, 1991; Whitley, 1989). The disadvantage of this method is that it requires sorting the entire population by rank which is a potentially time consuming procedure. In this method, sum of ranking is computed and then selection probability of each individual is computed as follows:

$$rsum_i = \sum_{i=1}^{N} r_{i,j} \tag{31}$$

$$PRANK_i = \frac{r_{i,j}}{rsum_i} \tag{32}$$

where i varies from 1 to $ngen$ and j varies from 1 to N

Elitism selection: Elitism selection in addition to many selection methods that force genetic operators to retain some member of the best individual at each generation. It improves the selection process and saves the best individuals. With elitist selection, the quality of the best solution in each generation monotonically increases over time. There is no doubt that without elitist selection, it is possible to lose the best individual due to stochastic errors (due to crossover, mutation, or selection pressure).

3) Genetic algorithm operators

GA uses two operators to generate new solutions from existing ones: crossover and mutation. These two operators work together to explore and exploit the search space by creating new variants in the chromosomes. In this subsection, we briefly describe each of these two terms in turn.

(a) Crossover

Crossover, also known as mating, is an important random operator in genetic algorithm. In crossover, two chromosomes from the mating pool are selected to be parents and exchange part of their genes to form two children. Crossover selects genes from parent chromosomes and creates a new offspring. Chromosomes with higher fitness have higher probability to be parents and pass genes to offspring. By iteratively applying crossover, genes of healthy chromosomes are expected to appear more in the population and make the population converge to good solution. Crossover operators are usually applied probabilistically according to a crossover rate. Typically, the crossover probability ranges from 0.6 to 0.95. Various crossover operators are available in the GA literature. The most commonly used crossover operators are the following: single-point crossover, two-point crossover, uniform crossover, and arithmetic crossover.

(b) Mutation

Mutation is an important component in GA, and is applied to introduce new genetic material into an existing individual as well as maintain genetic diversity in the population. This operator randomly flips or alters one or more gene values at a randomly selected location in a chromosome. This can result in entirely new gene values being added to the gene pool. With the new gene values, the GA may be able to arrive at better solutions than previously possible. Mutation can help genetic algorithms to escape local optima and in the search for global optima. Mutation operates independently on each individual by probabilistically perturbing each bit string. Typically, the probability for bit mutation is very small, ranging from 0.001 to 0.01 and depends on the length of the chromosome and population size. Several mutation operators have been proposed in the GA literature. The most commonly used mutation operators are the following: flip bit, boundary, non-uniform, uniform and Gaussian.

4.7 Evolutionary algorithms: State-of-the-art

Numerous evolutionary approaches to multi-objective optimization have been proposed in recent years (Coello Coello, 1999; Marler & Arora, 2004). These algorithms have some advantages and disadvantages when compared to each other but they have remarkable potential in solving MOOPs. This section briefly describes the working and salient features of six well-known evolutionary multi-objective algorithms: VEGA, MOGA, NPGA, SPEA, PAES, and NSGA-II. For details, readers are encouraged to refer to the original studies.

4.7.1 Vector Evaluated Genetic Algorithm (VEGA)

Schaffer (1985) proposed an extension of the simple genetic algorithm to accommodate vector-valued fitness measures, which he named it, the Vector Evaluated Genetic Algorithm (VEGA). VEGA is a population-based Pareto approach as well as the earliest (first) and yet the simplest multi-objective genetic algorithm. In this approach, the total population is divided into a number of populations equal to the number of objective functions to be optimized. Each population is used to optimize each objective function independently. The populations are then shuffled together followed by conventional crossover and mutation operators. However, VEGA has several drawbacks. Firstly, its selection process makes the population to converge to solutions superior at only one objective, but poor at others. Secondly, it does not incorporate diversity preservation, or elitism, which causes genetic drift to occur. Thirdly, VEGA uses fitness assignment strategies which are criterion-based and behaves as an aggregating approach ((Deb, 2001).

4.7.2 Multi-objective Genetic Algorithm (MOGA)

Fonseca and Fleming (1993) proposed a Pareto-based ranking procedure, where an individual's rank equals the number of solutions encoded in the population by which its corresponding decision vector is dominated. This procedure assumes the rank of a solution to be equal to one plus the number of solutions in the current population that dominate it. Consider, for example, an individual y_i at generation k, which is dominated by $p_i^{(k)}$ individuals in the current generation. The rank of an individual is given by Fonseca and Fleming (1993) as :

$$rank(y_i, k) = 1 + p_i^{(k)} \quad (33)$$

Therefore, all non-dominated individuals are assigned the highest possible fitness value, while dominated ones are penalized according to the population density in the corresponding region of the trade-off surface. The fitness assignment is based on the rank and niche count, which measures the density of the neighbourhood in objective space.

4.7.3 Niched Pareto Genetic Algorithm (NPGA)

Horn *et al.* (1994) developed an evolutionary multi-objective optimization algorithm based on a suggestion by Goldberg (1989). This method, known as Niched Pareto Genetic Algorithm (NPGA) uses a tournament selection method based on Pareto dominance. Two individuals are randomly selected for a tournament. To find a winner solution, a comparison set that contains several other individuals in the population is randomly selected. Then the dominance of both candidates with respect to the comparison set is tested. If one candidate only dominates the comparison set, he is selected as the winner. Otherwise, when both candidates are either dominated or non-dominated, a sharing procedure is implemented to specify the winner candidate. NPGA is easy to implement and efficient since it does not apply Pareto ranking to the entire population. NPGA also uses the niching technique as well as dominance ranking, while the diversity preservation is through kernel approach.

4.7.4 Strength Pareto Evolutionary Algorithm (SPEA)

Zitler and Thiele (1999) proposed the SPEA algorithm, which uses a mixture of established and new techniques in order to find multiple Pareto-optimal solutions in parallel. SPEA uses an archive containing non-dominated solutions previously found (external non-dominated set). At each generation, non-dominated individuals are copied to the external non-dominated set. For each individual in this external set, a strength is computed, which is similar to the ranking of MOGA (Fonseca & Fleming, 1993), since it is proportional to the number of solutions to which a certain individual dominates. Fitness of each member of the current population is computed according to the strengths of all external non-dominated solutions that dominate it. Pareto dominance as opposed to niches based on distance, is used to ensure that the solutions are properly distributed along the front.

4.7.5 Pareto Archived Evolution Strategy (PAES)

Knowles and Corne (2000) proposed a simple evolutionary algorithm called Pareto Archived Evolution Strategy (PAES). PAES consists of a (1+1) evolutionary strategy (i.e. a single parent that generates a single offspring) in combination with a historical archive that records the non-dominated solutions previously found. This archive is used as a reference set against which each mutated individual is being compared. Stated differently, in PAES one parent generates one offspring by mutation. The offspring is compared with the parent. If the offspring dominates the parent, the offspring is accepted as the next parent as the iteration continues. On the other hand, if the parent dominates the offspring, the offspring is discarded and a new mutated solution (new offspring) is found. However, if the offspring and parent do not dominate each other, a comparison set of previously non-dominated individuals is used. To maintain population diversity along Pareto front, an archive of non-dominated solutions is considered. The new generated offspring is compared with the archive to verify if it dominates any member of the archive. If yes, then the offspring enters the archive and is accepted as a new parent. The dominated solutions are eliminated from the archive. If the offspring does not dominate any member of the archive, both the parent and offspring are checked for their nearness with the solution of the archive.

4.7.6 Non-dominated Sorting Genetic Algorithm II (NSGA-II)

Presented by Deb *et al.* (2000), the elitist Non-dominated Sorting Genetic Algorithm-II (NSGA-II) is one of the most widely used algorithms for solving multi-objective optimization problems. It is an improved version of the non-dominated sorting genetic algorithm NSGA (Srinivas & Deb, 1994),which has been generally criticized for its computational complexity, lack of elitism, and the need for specifying a sharing parameter (Deb *et al.*, 2000; Deb *et al.*, 2002). NSGA-II has been shown to have a better sorting algorithm, incorporates elitism and no sharing parameters needs to be chosen prior. Moreover, the algorithm uses a non-domination sorting approach to classify solutions according to the level of non-denomination and a crowding distance operator to maintain solution diversity across approximate solution sites. Additionally, its salient features such as elite preservation and explicit diversity preserving mechanism ensure its good convergence and diversity. Notably, NSGA-II is also an extension of the Genetic Algorithm for multiple objective optimization. Furthermore, it is related to sibling evolutionary algorithms such as VEGA, SPEA, and PAES.

4.7.7 Selection of optimization method

The previous section has discussed the various evolutionary algorithms for multi-objective optimization. It is clear from the discussions that all of these algorithms give some guarantee on convergence to the Pareto front. One of them is an incremental improvement of its predecessor. VEGA is the oldest algorithm of the six, but its selection process makes the population to converge to solutions superior at only one objective, but poor at others. In addition, VEGA does not incorporate diversity preservation, or elitism, which causes genetic drift to occur. MOGA is the second oldest algorithm of the six, but while it uses depreciated diversity metric, its convergence cannot be entirely dismissed as inferior to the rest. NSGA-II has been found to be one of the best known multi-objective evolutionary algorithms, extensively used in many studies (Zitler *et al.*, 2002). Moreover, it has been shown to perform better than other state-of-the-art evolutionary algorithms with the same goal of finding diverse Pareto optimal solutions such as PAES and SPEA (Kollat & Reed, 2006; Tang *et al.*, 2006). For these reasons, the NSGA-II is selected in this study and the MOISAT (multi-objective optimization and integrated sustainability assessment tool) is built upon this.

NSGA-II is suitable for the present work because of the following key features: (1) lower computational complexity and higher efficiency; (2) a non-dominated sorting procedure where all individuals are sorted according to the level of non-domination; (3) its ability to implement elitism which stores all non-dominated solutions, and hence enhancing convergence properties and the probability of creating better offspring solutions and thus increase the searching efficiency and save time; (4) it adapts suitable automatic mechanics based on the crowding distance in order to guarantee diversity and spread of solutions, consequently, user-specified sharing parameters such as niche size are not needed in this algorithm so that the method is not susceptible to the different values of the sharing parameter; and (5) constraints are implemented using modified definition of dominance without the use of penalty functions. Deb *et al.* (2002) also argue that NSGA-II outperforms other widely used contemporary multi-objective genetic algorithms embedded with diversity preservation and elitism features in terms of nearness to the true Pareto front and diversity of the solutions. Thus, based on the above, NSGA-II was deemed appropriate for the present study.

The NSGA-II working procedure is illustrated in Figure 4.4. The algorithm starts with a random population of input variables P_t . Then population R_t at time *t* is created by population P_t and Q_t (which is created from the parent population P_t (size N) by using usual genetic operators-selection, crossover, and mutation). After that entire population R_t evaluated by objective functions and based on non-dominated procedure, all members of R_t are classified according to the ascending order of dominance. Then, the best Pareto fronts (which are stored on top of the list) are transferred to the new parent P_{t+1}. This operation is called elitism. Since, the size of population P_{t+1} is half of R_t (infact size of P_{t+1} is equal to the size of P_t), the half of Pareto fronts are deleted during the transferring. The procedure is continued until all individuals of a particular Pareto front cannot be accommodated entirely in the parent population P_{t+1}. Therefore, for choosing the exact number of individuals of that particular front for filling remained space of the population P_{t+1}, crowded comparison operator which is called crowding distance is employed. Finally, the individuals which have more distance than other individuals in the particular Pareto (individuals with less density) are selected to fill the rest of the parent population P_{t+1}. It should be noted that crowding distance operation lead to more diversity of the solutions in the Pareto front. At the end, population P_{t+1} will be utilised instead of population P_t on the next generation of NSGA-II and optimal Pareto front will be determined after particular generation.

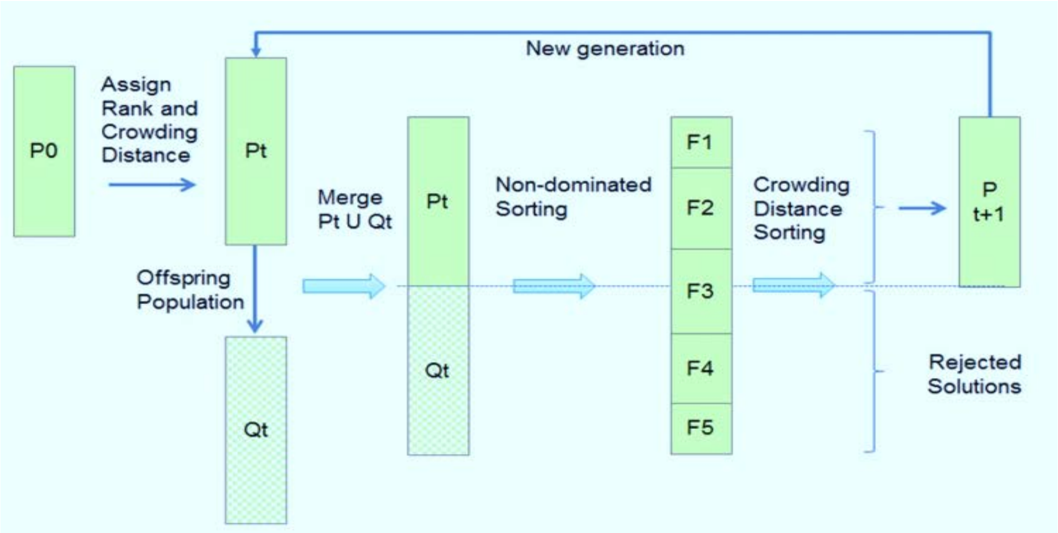

Figure 4.4: NSGA-II working procedure. Source: Deb *et al.* (2002)

4.8 Constraint handling

This section presents a brief review of constraint handling techniques used in multi-objective evolutionary optimization. Real-world optimization problems have constraints that must be satisfied by the solution of the problem. To solve a constrained multi-objective optimization problem, an algorithm should tackle the objective functions and constraints simultaneously. As a result, a variety of constraint-handling techniques targeted at evolutionary algorithms has been proposed in the specialized literature. The reader is referred to the following surveys (Coello Coello, 2002; Coello Coello & Carlos, 1999; Dasgupta & Michalewicz, 1997; Gen & Cheng, 1996; Michalewicz, 1995a, 1995b; Michalewicz & Schoenauer, 1996; Yeniay, 2005) for further details, explanations and comparison. Coello Coello (2002) gives an excellent survey on the constraint handling techniques used in evolutionary algorithms.

Constraint-handling methods for evolutionary algorithms can be broadly categorized in five different types: (i) penalty function approach, (ii) separation of constraints and objectives, (iii) special representation, (iv) repair algorithms, and (v) hybrid methods. Penalty methods were originally proposed by Courant (1943) and later expanded by Carrol (1961), and Fiacco and McCormick (1966). The penalty function approach transforms a constrained problem into an unconstrained one (or a series of unconstrained problems). These are incorporated into the objective function by means of a “penalty parameter”, which penalizes any constraint violation. Then a certain value is added (or subtracted) from the objective function of the unfeasible solutions based on the extent of constraint violation. Penalty function methods are the commonly used methods for handling constraints using evolutionary algorithms due to their simplicity of implementation, general applicability, and strong theoretical basis (Coello Coello, 2002). However, the main limitation of penalty function methods is that they require fine tuning of the penalty factors (Wang & Cai, 2012).

To address this issue, Debchoudhury *et al.* (2013) proposed a modified penalty function, free from scaling parameters that finds the penalty terms based on the constraint violation and the fitness functions of the infeasible solutions. Datta *et al.* (2013) introduced another penalty function approach, which is able to further improve the best solutions by decreasing the level of constraint violation using a gradient free pattern search method. Montemurro *et al.* (2013) proposed the automatic dynamic penalization method in which all the information needed for tuning the penalty parameters is extracted from the population members of the current generation. In addition, some other studies choose the parameters of the penalty functions adaptively (Costa *et al.*, 2013; Vargas *et al.*, 2013; Wang *et al.*, 2014).The focus of these studies is to make the penalty functions independent of any external parameters. Penalty function approach is subdivided into several subcategories (e.g., static, dynamic, adaptive, co-evolutionary, etc.) based on the method of penalty factor handling (Coello Coello, 2000b; Hoffmeister & Sprave, 1996; Homaifar *et al.*, 1994; Joines & Houck, 1994).

Deb *et al.* (2002) proposed a feasibility approach for handling inequality constraints, which considers the constraints and objectives separately. It selects a feasible solution over an infeasible solution during the selection step in the generations. Constraint handling using special representation is employed for particular types of optimization problems, whereas repair algorithms convert the infeasible individual into a feasible or less feasible individual (Harada *et al.*, 2007). Finally, in the hybrid approach, constraint handling is tied with some other optimization approach. Of the five categories of constraint handling methods, penalty function and feasibility approaches have been popular for solving constrained MOO problems in industrial applications.

The feasibility approach can handle equality constraints via suitable transformation into inequality constraints, but this requires different values of tolerance limit for different constraints in the same problem and also for different problems. Takahama and Sakai (2006) proposed e-constraint DE, where equality constraints are relaxed systematically. Zhang and Rangaiah (2012) proposed adaptive constraint relaxation and feasibility approach (ACFRA) for handling constraints in single objective optimization (SOO). In this approach, individuals with total constraint violation less than the limit are temporarily considered as feasible individuals during selection for the next generation. This violation limit is changed dynamically based on the performance of the search. In this study, AC, as proposed by Deb *et al.* (2002), is modified for solving constrained MOO problems. It is implemented in the NSGA-II and tested on three benchmark functions with equality and inequality constraints.

4.9 Chapter summary

This chapter provided an overview of different aspects of multi-objective optimization. First, the decision-making context in which multi-objective optimization can be a useful alternative to solve complex problems has been presented. Second, the basic concepts used in multi-objective optimization have been provided. The formulation of a general multi-objective optimization problem on which MOISAT will be devised, is introduced. Next, the concept of Pareto optimality and Pareto dominance is also introduced. The review has established that multi-objective optimization is different from single objective optimization. For conflicting objectives, the results of multi-objective optimization give rise to a number of optimal solutions, known as Pareto optimal solutions or non-inferior solutions. Given that none of these solutions can be said to be any better than others, the first task in an ideal multi-objective optimization, is to find as many such Pareto optimal solutions as possible.

This chapter has also described the classical optimization methods of multi-objective optimization. The classical methods of solving multi-objective optimization consists of converting the multi-objective problem either by scalarizing (aggregating) the objective functions or optimizing one objective and treating the other as constraints. The weighted sum method converts multiple objectives into a single objective by using a weighted sum of objects. The weights are user defined and therefore the obtained solution largely depends on the choice of the weight vector used in the scalarization process. However, since this approach is incapable of finding trade-off optimal solutions in problems with non-convex Pareto optimal region, the $\boldsymbol{\varepsilon}$-constraint method converts all but one of the objective functions into constraints. Again, user-defined limits are used to constrain the objectives.

Another way to solve multi-objective optimization problems is by using the goal programming method. In goal programming (GP), the objectives are formulated as goal criteria that the decision-maker desires each objective to possess. These values are incorporated into the problem as additional constraints. There are difficulties when using classical methods in tackling multi-objective optimization problems, which leads to the conclusion that classical methods are not suitable for the proposed MOISAT model. In this chapter, genetic algorithms, one of the most popular evolutionary algorithms has been presented. Following is a brief description of the working and salient features of six well-known evolutionary multi-objective algorithms: VEGA, MOGA, NPGA, PAES, SPEA, and NSGA-II. Finally, NSGA-II is selected to be used in the proposed model to optimize tea operations and processes. The next chapter provides a comprehensive discussion of the research methodology underpinning this dissertation.

Chapter-5
Research Methodology

5.1 Introduction

This work was conducted in order to develop a multi-objective optimization tool to support decision-making processes in the Malawian tea industry. The present chapter describes the research methodology adopted for this study. The research approach for this study followed core research activities of literature review, research design, modelling, case studies, validation, and conclusion. Various research techniques such as industrial surveys, case studies, and statistical analysis, were applied to achieve the research objectives. The first section briefly reviews the philosophical assumptions underpinning this research study, discussing the researcher's pragmatic stance and the consequent choice of the mixed-method approach. The chapter then proceeds to explain the research design adopted in this study. The next section discusses the rationale for the choice of research strategy with explanation of the research methods used in this study. The chapter further presents a detailed description of the research process, data collection and analysis, and the application of data analysis. The research design for this study was a combination of exploratory and descriptive design. The chapter closes with a discussion of the strategies that were used to enhance the validity, reliability and trustworthiness of the study.

5.2 Philosophical underpinnings

Research philosophy is unquestionably the bedrock of any scientific inquiry and represents the researcher's guiding assumptions about the nature of the world (Easterby-Smith *et al.*, 2008). Moreover, it guides the researcher in making the right decisions about the approach, strategy, data collection techniques and procedures on how to answer the research questions (Omotayo & Kulatunga, 2015). Saunders *et al.* (2012) defines research philosophy "as the manner in which knowledge is developed and interpreted". Creswell (2013) describes research philosophy as a belief about the way in which data about a phenomenon should be gathered, analysed and used. Williams and May (2002) have identified three philosophical values which define the various disciplines: ontology, epistemology, and axiology. According to these authors, epistemology describes "how" a researcher knows about the reality and assumptions about how knowledge should be acquired and accepted. Ontology explains "what" knowledge is and its assumptions about reality (raises questions on how they found functions and various views that people hold within), while axiology reveals the assumptions about the value system. No question, these philosophical values complement the formulation of research philosophy, thereby influencing the selection of appropriate research approach and methods (Saunders *et al.*, 2012).

Moreover, research methods are grounded in philosophical traditions that stem from the researcher's paradigm (Guba, 1990). Paradigms are sets of beliefs, values, practices and assumptions, shared by a community of researchers, which regulate the nature and conduct of research within disciplines (Haase & Myers, 1988; Kuhn, 1970; Munhall, 1982). Guba and Lincoln (1994) note that these beliefs include the nature of reality (ontology), how we gain knowledge about what we know (epistemology), what values go into it (axiologic), how we write about it (rhetoric), and the process of research (methodology). Paradigms act as a lens that the researcher uses to view the world; therefore, it reflects the worldview of the researcher. The beliefs or traditions thus frames the philosophical stance of the researcher and determines, to a large extent, the choices of how the research will be conducted (Guba, 1990).

The research philosophy adopted for this study was based on the pragmatic paradigm as explicated by (Feilzer, 2010). The researcher believes the pragmatic research paradigm is more appropriate to address the research question and to achieve the objectives of this study. The pragmatic research approach was selected because it advocates the use of mixed methods in research; avoids the heavily contentious issues of truth and reality (Feilzer, 2010); and focuses instead on what works as the truth regarding the research questions under investigation (Tashakkori & Teddlie, 2009). Pragmatism focuses on the research problem instead of focusing on methods and uses all approaches available to understand the problem (Creswell, 2005). Consequently, the researcher is at liberty to choose data collection methods that are most likely to provide insights into the question with no philosophical loyalty to any alternative paradigm. Additionally, pragmatism supports researchers in choosing between different paradigms as the research questions being addressed intrinsically determine which paradigms are best suited. Some research questions are best addressed using positivism while the interpretivism approach is used for others. The pragmatic philosophy underpinning this study allowed a systematic application of positivism and the interpretivism approach to address the specific objectives.

5.3 Research design

The research design applied in this study is a combination of exploratory and descriptive design. Bless *et al.* (2006) stated that the main purpose of an exploratory research is “to gain insight into a situation, phenomenon, community or a person”. Kumar (2011) indicates that an exploratory design is conducted when a problem has not been clearly defined, or the study topic is either new, or relatively little has been written about it, as is the case with the focus of this particular study. Kumar further notes that exploratory research is conducted with goals intended to: (i) scope the magnitude or extent of a particular phenomenon, problem, or behaviour; (ii) generate some initial ideas about that phenomenon, or (iii) test the practicality of undertaking a more extensive study regarding that phenomenon. Rubin and Babbie (2013) explained, “the exploratory design is linked to the purpose of the study, with the main aim being to explore the topic and to provide a certain level of familiarity with it.” Thus, an exploratory research helps to determine the best research design, data collection methods and selection of subjects. Furthermore, the explorative design was adopted in this study in order to explore the needs of respondents, and with the aim to direct the study towards a descriptive design. The main purpose of the study remains descriptive in nature and this was fully implemented in the quantitative part of the study.

Descriptive research, on the other hand, describes data and characteristics about the population or phenomenon being studied. Kumar (2011) points out that descriptive research aims to describe a situation, problem or phenomenon systematically, or provides information about, say, the living condition of workers in tea plantations, or describes attitudes towards an issue. Bless *et al*., (2006) adds that descriptive research is applied “when the researcher is interested in determining the opinion of a group of people towards a particular issue at a particular time”. The main objective of this study is to develop a multi-objective optimization tool to support decision-making processes in the tea industry. The study is firstly explorative because the researcher sought to identify factors that influence the productivity of tea industry in Malawi. The study also assessed the level of awareness as well as the extent of implementation of sustainability practices in the tea industry and the likely effects this may have on business performance by surveying the perceptions of decision makers. Secondly, the study will be descriptive in nature. The study used a survey-based research method to describe the existing situation of the Malawian tea industry in terms of current trends and shifts in relation to the sustainability concept and reveals how the tea industry can cope with market shifts and challenges with the help of multi-objective optimization modelling. As such, the researcher intended to describe the existing situation of the Malawian tea industry with regard to sustainable production practices, its environmental and social impacts. Thus, based on the above, the two research designs were deemed appropriate for the present study. Cross sectional design is used in the present study as the information from any given sample of population element is collected once.

5.4 Research strategy

The research strategy for this study is a combination of survey research and multi-case study approach. Saunders *et al.* (2012) defined research strategy as “the general plan of how a researcher will go about answering the research questions”, while Bryman (2008) has referred to it as “a general orientation to the conduct of research”. Research strategy, according to Remeyi *et al.* (2003), provides the overall direction of the research including the process by which the research is conducted. Saunders *et al.* (2012) mentioned that appropriate research strategy has to be selected based on research questions and objectives, the extent of existing knowledge on the subject area to be researched, the amount of time and resources available, and the philosophical underpinnings of the researcher. Yin (2003) stresses three conditions upon which selection of a particular strategy has been based on: the type of research question, the extent of control an investigator has over actual behavioural events and the degree of focus on contemporary or historical events.

Researchers may select from various research strategies, based on the above criteria. Obviously, they do overlap and hence the important consideration would be to select the most advantageous strategy for a particular research study. Common research strategies used in business research include experiment, survey, case study, action research, grounded theory, ethnography, archival research, cross sectional studies, longitudinal studies, and participative enquiry (Collis & Hussey, 2009; Easterby-Smith *et al.*, 2008; Remeyi *et al.*, 2003; Saunders *et al.*, 2012). Each strategy is suitable for different contexts, but Yin (2003) defines three questions that need to be considered before a choice is made: (1) what type of research question has been defined; (2) the researcher's ability to affect the outcome; and (3) focus on current or historical events.

To achieve the research objectives, the descriptive cross-sectional survey was selected, because it allows data collection from a sample which is statistically representative (Owens, 2002) and makes use of various data collection methods, including questionnaires, interview methods. Furthermore, the survey strategy provides findings that are well defined, can be explained, and portrayed numerically (Collis & Hussey, 2009). Owens (2002) posits that surveys provide a quick and accurate means of accessing information on a population at a single point in time. More importantly, the research method is frequently used in research involving attitude survey, and to identify what managers do and think about a specific issue being studied. The present study sought to identify the opinions, experiences and behaviours of managers in the Malawian tea industry, thus a descriptive survey approach was deemed the most appropriate strategy.

This study also utilized an explorative and descriptive multi-case study strategy. The basis for selecting such an approach can be comprehended in several steps. Firstly, a case study approach is the most suitable method when the research problem addresses the question of "how do" rather than "how should" and therefore, the inductive approach is required to solve the problem. Secondly, the strategy allows investigations to retain the holistic and meaningful characteristics of real-life events such as organizational and management experiences. Thirdly, the multiple case study design was preferred over the single case design because it provided robust and rigorous grounds for good quality research derived from triangulation of evidence compared with single case design (Eisenhardt, 1989; Yin, 2003). Fourthly, the evidence abstracted from multiple case research is considered more powerful and more compelling (Herriot & Firestone, 1983) and the approach is a very useful tool to gain insight into all aspects of how tea industry in Malawi address complex strategic decision making regarding sustainable productivity (Herriot & Firestone, 1983).

5.5 Research methods

Blaikie (1993) defines research methods as being: "the actual techniques and procedures used to gather and analyse data related to some research questions or hypothesis." More specifically, methods indicate steps (or actions, phases, step-wise approaches) that a researcher should follow in conducting the research. This study combined qualitative and quantitative methods in order to capitalize on the strengths of each approach. The quantitative method was appropriate for this study because of several reasons: (i) allows the research problem to be conducted in a very specific way and set of terms; (ii) clearly and precisely specifying both the independent and the dependent variables under investigation; (iii) achieving high levels of reliability of data gathered due to controlled observations, mass surveys, or other forms of research manipulation; and (iv) follows resolutely the original set of research goals, arriving at more objective conclusions, testing hypothesis, determining the issues of causality and eliminates or minimizes subjectivity of judgment (Kealey & Protheroe, 1996).

In addition, qualitative data collection methods were used in this study in order to explore the experiences, perceptions and views of decision-makers in the tea industry in relation to the concept sustainable productivity. Bryman and Bell (2011) hold the view that qualitative methods often refer to case studies where the collection of information can be received from a few studying objects. They further argue that qualitative research is an appropriate approach for research in business and management. Ghauri *et al.* (1995) highlight that qualitative methods emphasize on understanding, interpretation, observations in natural settings and closeness to data with a sort of insider view. Qualitative research method was suitable for this study due to the following key strengths: (i) obtaining a more realistic feel of the world that cannot be experienced in the numerical data and statistical analysis used in qualitative research; (ii) flexible ways to perform data collection, subsequent analysis, and interpretation of collected information; (iii) provide a holistic view of the phenomena under investigation; ability to interact with the research subjects in their own language and on their terms; and (iv) descriptive capability based on primary and unstructured data (Matveev, 2002). Thus, based on the above, a combination of the two research methods was deemed appropriate for the present study.

5.6 Data collection methods

Polit and Beck (2010) define data collection as “the gathering of information needed to address a research problem”. In order to accomplish the research objectives and to address the research questions, this study utilizes both primary and secondary data collection methods. Maholtra (2006) describes primary data as data originating from the researcher for the specific purpose of addressing the research problem. Secondary data, on the other hand, comprises information that has already been collected, assembled and interpreted by other researchers or organizations, archived in some form such as, literature, documents and articles (Bryman & Bell, 2011). There are various methods that can be employed in gathering information from different sources such as tests, the questionnaire, interviews (unstructured, structured and semi-structured), direct observations, gathering of documentation and artefacts, focus groups, and existing or secondary data (Easterby-Smith *et al.*, 2008; Saunders *et al.*, 2012). The methods of data collection in this study were based on questionnaires, interviews, document analysis, and direct observations. Triangulation of data sources was adopted in this study with the purpose of increasing the quality and validity of the research (Easterby-Smith *et al.*, 2008; Patton, 2002; Stake, 1995).

5.6.1 Primary research methods for data collection

This study is predominantly a quantitative study and a descriptive cross-sectional survey research design was used to collect data as well as describe the information about the Malawian tea industry. The study is also exploratory and descriptive in nature. A descriptive cross-sectional survey collects data to make inferences about a population of interest; this information provides snapshots of the populations from which researchers gather data. In addition, the survey assists the researcher to establish whether significant associations among variables exist at one point in time, depending on the resources available and the target population. Moreover, a descriptive cross sectional survey affords the opportunity to capture a population's characteristics and test hypotheses quantitatively and qualitatively.

Primary data for the descriptive part of this study was collected using a structured questionnaire. The purpose of the structured questionnaire survey was to elicit respondents' perceptions about opinions, attitudes, knowledge, awareness and motivations for sustainable productivity of the Malawian tea industry. Oppenheim (1992) defined a questionnaire as a tool for collecting and recording information about a particular issue of interest. A structured questionnaire survey was chosen because of the following advantages: (i) it is simple to administer; (ii) data obtained is reliable; and (iii) the coding, analysis and interpretation of data are relatively simple and straight forward (Maholtra, 2006). Cohen *et al.* (2000) add that it is cost and time efficient in terms of collecting and analysing data. Furthermore, the primary advantage of using a questionnaire was that it allowed the researcher to access a large sample group and to offer the respondents the convenience of when and where to complete it (Punch, 2003).

Moreover, the structured questionnaire approach was the most appropriate choice, as data on sustainable productivity has not been previously collected at the tea firms studied within this research. Additionally, the structured questionnaire approach to primary data collection is seen to be important as it provides the tea industry with information on which to act (Oppenheim, 1992). Finally, a structured questionnaire makes it easier for the researcher to perform statistical analysis. In addition, it also simplifies turning the data analysis into quantitative results that can be used for decision-making. Perhaps one of the major weaknesses of using the structured questionnaire is the lack of in-depth data collection from participants, as the researcher does not physically interact with or even observe the participants. Another drawback of this method is the use of closed ended questions which limits the in-depth enquiry of relevant information (Easterby-Smith *et al.*, 2008).

5.6.2 Secondary research methods of data collection

Secondary research is research based on secondary sources that already exist (Babbie & Mouton, 2012). Secondary data, which formed the literature review, was collected from different sources, including publications and reports of the Tea Association of Malawi (TAML), Tea Research Foundation Central Africa (TRFCA), Limbe Auction Floors, and National Statistical Office, Food and Agriculture Organization Statistics (FAOSTAT) database, and individual tea companies. Other information related to the industry has been collected from unpublished works like doctoral theses, research reports, books, periodicals, journal articles, and other various documents of tea companies.

5.7 Population and sampling

Graziano and Raulin (2000) stated that "sampling is the process of systematically selecting a portion of the population to represent the entire population". Rubin and Babbie (2013) described the sample unit as that element, or a set of elements, that will be considered for selection at some stage of sampling. Neuman (2011) argued that a sample represents the population and is more manageable to work with than the whole population or pool of cases. Neumann stressed that well-executed sampling enables the researcher to measure variables on the smaller set of cases, and to generalize results accurately to all cases. The overall purpose of sampling is to achieve representativeness. Clearly, researchers should carefully select a sample in such a way as to be representative of the population from which it is taken. Cooper and Schindler (2014) suggested that in designing the sample, the following should be performed: the target population, parameters of interest, sampling frame, the appropriate sampling method and the required sample.

5.7.1 Study population

Creswell and Plano Clark (2010) define population as "a group of individuals who possess specific characteristics and from which a sample is drawn to determine the parameters or characteristics," whereas Bryman and Bell (2011) highlights population as "the universe of units from which the sample is selected". Population can also be defined as the study subjects (employees, managers) or study units (tea factories) that are the focus of the research project. The individual units of analysis that are chosen, therefore, represents the total study population that generalizes the research problem and towards which the results will be generalized. Rubin and Babbie (2013) described units of analysis as people or things in the population whose characteristics are observed, described and explained by social research. The unit of analysis applied to this study was a sample of tea factories in Malawi.

The target population of this study consists of all 11 private held tea companies in Malawi. However, some stakeholders within the tea industry's value chain were also targeted to provide the required information collected through the questionnaire. The study population therefore comprised 4 managing directors, 2 engineering directors, 7 group (estate) managers, 10 production managers, and 10 factory engineers. Through the structured questionnaire distributed by the researcher, individuals familiar with the operations of tea plantations were able to give the researcher more information and insights about tea production and processing operations.

5.7.2 Sampling frame

In order to construct a systematic sample, it is necessary to use a sampling frame. Rubin and Babbie (2013) define sampling frame as “a list of the population from which a sample is drawn”. The sample frame for this study consisted of all tea companies operating in Malawi, drawn from the records of the Tea Association of Malawi (TAML). TAML is the official body representing the tea industry in Malawi and all tea companies are members of this association. The directory compiled by TAML was identified as an attainable list of the accessible population, and therefore a suitable sampling frame for the purpose of this study. The sample frame of this research included a representative sample of the individuals (directors, managers, employees) of these tea companies. There were eleven (11) private held tea companies in Malawi, owning forty-four (44) estates and operating twenty-one (21) tea processing factories. Table 5.1 shows the population of factories in which the sample was drawn. In addition, three groups of respondents, namely, managers and stakeholders, participated in this study by providing the required information.

Table 5.1: Summary of accessible population, sample size by factories

Company	Factories	Factories sampled	Sample size					
			MD	ED	GM	PM	FE	Total
Eastern Produce	9	5	1	1	4	5	5	16
Lujeri	3	2		1		1	1	3
Makandi	1	1	1		1	1	1	4
Naming’omba	2	1	1		1	1	1	4
Steco	1	1	1		1	1	1	4
Conforzi	1	1				1	1	2
Others	4	0						
Total	21	11	4	2	7	10	10	33

MD = Managing Director, ED = Engineering Director, GM =Group Manager

PM = Production Manager, FE = Factory Engineer

5.7.3 Sampling techniques

Sampling designs can be classified as either probability or non-probability sampling. Probability sampling is undoubtedly the most frequently used method and involves random selection of elements, where each element has an equal probability (chance) of being included in that sample. Non-probability sampling, on the other hand, is a technique wherein the elements are gathered in a process that does not give all individuals in the population equal chances of being selected in the sample. In other words, non-probability sampling implies that the chances of each element to be chosen in the sample are unknown but the features of the population are used as the main measure for selection. However, most business and management studies use non-probability sampling, especially purposive sampling, to select study samples.

There are five well-known and recognised types of non-probability (non-random) sampling designs: convenience (accidental), purposive (judgmental), snowball (network), quota, and consecutive (Creswell, 2013; Kothari, 2005; Leedy & Ormrod, 2010; Saunders *et al.*, 2012). Although these differ, they each have strengths and weaknesses as well. An exhaustive discussion of these techniques is beyond the scope of this section. This study adopted the purposive sampling technique, to select study participants and cases that would serve the purpose of the study and answer the research questions posed at the beginning of this dissertation. Parahoo (2006) describes purposive sampling as “a method of sampling where the researcher deliberately chooses who to include in the study based on their ability to provide necessary data”.

Purposive sampling was the most appropriate technique for part of this study, because it allowed the researcher to use personal judgment to select study participants that would give particular information as well as best meet the research questions and objectives (Saunders *et al.*, 2012). In addition, purposive sampling was the preferred technique since the aim of this study was to identify a particular predetermined type of industry, namely tea, for in-depth investigation. Saunders *et al.* (2012) also recommended this technique when working with small samples as what happens in case studies. Bless *et al.* (2006) asserted that purposive sampling is used when a sample chosen for a specific reason to provide insights into a particular field of interest, and determined by the research topic. Welman and Kruger (2001) consider purposive sampling as the most important kind of non-probability sampling to identify the primary participants.

5.7.4 Sample size and sample adequacy

In this study, the sample size was determined by considering the representativeness of the sample of the target population. To determine the specified sample size and sample elements, the study considered factors such as accessibility, convenience and cost of reaching the sampled tea factories. Six (6) tea companies in Malawi were selected using the TAML Directory. The sample formed about 55% and 38% of tea companies and factories, respectively, in Malawi and was found to be adequate for the purpose of this study. Hussey and Hussey (1997) and Robson (2002) purport that there is no ideal or prescribed sample size, for the correct sample size depends upon the purpose of study and the nature of the population under study. According to Gall *et al.* (2005), a sample size of 30% is held by many to be the minimum number if the researcher plans to use some form of statistical analysis on their data. Thus, 30% of the accessible population was considered enough for the sample size.

5.8 Data analysis

Polit and Beck (2010) describe data analysis as “the systematic organization and synthesis of research data, and the testing of a research hypothesis using that data. Methods of data analysis can differ according to the research objectives. They can either take a qualitative or a quantitative approach. In this study, a quantitative approach was used as the main method for quantifying and analysing the data. The quantitative and qualitative data in this study were analysed by applying appropriate and relevant data analysis techniques suggested in literature for each type of data collected. Statistical analysis was carried out on the eight factories that participated in this study. This research study was, to a large extent, descriptive in nature and therefore both descriptive and inferential analyses were used. De Vos *et al.* (2005) argue that descriptive statistics summarize patterns while inferential statistics help to establish whether findings from a sample can be extrapolated to a wider population. The questionnaire was coded and analysed to produce nominal data variables, which were then entered into a spreadsheet. The primary data collected from the respondents were tabulated and analysed using Statistical Package for the Social Scientists (SPSS) Version 20 for windows. The nominal data was then analysed in terms of frequency distribution, which was a method of tallying and representing how often certain results occurred. Considering that the research and survey population was small, a non-parametric test for determination of statistical significance was considered inappropriate and therefore not used.

5.9 Data validity and reliability

This section discusses the quality of research in terms of validity and reliability. Data validity and reliability are the critical foundations of scientific work. Meticulous adherence to these two aspects can make the difference between good and bad research and can assure that other researchers accept findings as credible and trustworthy. The following subsections define these terms and explain the steps taken to ensure that data contained in the present study is valid and reliable.

5.9.1 Data validity

Data validity is concerned with the “methodological soundness or appropriateness, and refers to whether the concepts being investigated are actually the ones being measured or tested”. In other words, it refers to whether or not the data collected actually represent that which they purport to represent. Thus data validity serves as a framework for assessing the quality of research conclusions (Trochim, 2006). Welman and Kruger (2001) describe validity “as a mechanism that ensures that the process implemented to collect data has collected the intended data successfully”. Babbie (2013) defines validity as “the extent to which an empirical measure adequately reflects to the real meaning of the subject under investigation. On the same note, Remeyi *et al.* (2003) refers to validity as representing a good fit between theory and reality, in the same sense that when a description of a process is evaluated; best fit between theory and reality can be traced. Joppe (2000) argues that validity determines whether the research truly measures that which was intended to measure or how truthful the research results are. To put it bluntly, validity is the degree to which a research study measures what it intends to measure or degree to which an instrument succeeds in measuring what it has set out to measure.

Sekaran (2003) identified four different types of validity: content, criterion, construct, and face. Content validity deals with how the content and cognitive processes included can be measured. Topics, skills and abilities should be prepared and items from each category randomly drawn. Criterion validity refers to the relationship between scores on a measuring instrument and the independent variable (criterion) believed to measure the behaviour of the characteristics in question directly. The criterion should be relevant, reliable and free from bias and contamination. The construct validity of a measuring instrument refers to the extent to which the test measures a specific trait or construct, for example, intelligence, reasoning, ability and attitudes. Face validity, on the other hand, indicates that the items that are believed to measure a concept, on the face of it, must appear to be measuring the items.

In order to ensure that data obtained was valid in the present study, the author took the following steps. The researcher undertook an extensive literature review with a view to understand how personal interviewing and industrial surveys are conducted. Simple and clear instructions were given on how to complete the questionnaire. This ensured that the interviewer focused on the topic under discussion. Secondly, the purpose of the study was clearly explained to the respondents and issues of concern were resolved satisfactorily. The procedure of the interview was explained to the respondents. Finally, respondents were assured of confidentiality. This encouraged frankness during the interview. These steps ensured that the interviews were conducted in an environment acceptable to the respondents, and therefore ensured that the process was trustworthy.

5.9.2 Data reliability

Data reliability is concerned with the quality of measurement, with how consistent the measurements are or how reproducible the set of results are (Trochim, 2006). It refers to the consistency of data obtained. Joppe (2000) defines reliability as "…the extent to which results are consistent over time and accurate representation of the total population understudy is referred to as reliability and if the results of the study can be reproduced under a similar methodology, then the research instrument is considered to be reliable." It is important to note the idea of replicability or repeatability of results or observations in this definition.

Reliability, as defined by Babbie (2013), is "a condition in which the same results will be achieved whenever the same technique is repeated to do the same study. Kirk and Miller (1986) identify three types of reliability referred to in quantitative research, which relate to: (1) the degree to which a measurement, given repeatedly, remains the same; (2) the stability of a measurement over time, and (3) the similarity of measurement within a given time period. Blumberg *et al.* (2005) mention two types of reliability: test-retest (coefficient of stability) and internal consistency. According to these authors, consistency (in the test-retest method) is estimated by comparing two or more repeated questions of the measuring instruments. This gives an indication of the dependability of the result on one occasion, which may then be compared with the results obtained in another occasion. On the other hand, internal consistency reliability indicates how well the test items measure the same thing.

However, qualitative researchers view the concepts of reliability and validity differently. Merriam (2009), for example, contends that the concepts of validity and reliability are quantitative, positivist and inadequate, and not necessarily that applicable to the qualitative research paradigm. Hoepfl (1997) argues strongly that precision, credibility, and transferability provide the lenses of evaluating the findings of qualitative research. Creswell (2005) and Guba and Lincoln (1994) suggest four strategies to establish the trustworthiness of qualitative research: credibility, transferability, dependability and conformability. These constructs compare to the quantitative criteria of validity, reliability and neutrality.

In order to achieve a high level of reliability in this study the researcher took the following steps: firstly, the researcher did not influence the participants to support his views when giving their responses. Secondly, the data collected for this study was treated in the strictest of confidence. Thirdly, tea companies that participated in this study were assured that the information gathered would be treated as strictly confidential. Finally, a rapport with the respondents was successfully established during the fieldwork stage. The researcher began to build a relationship of trust with the respondents, and the credibility of the study was reinforced.

5.9.3 Ethical considerations

Polit and Beck (2010) describe research ethics as “a system of moral values that is concerned with the degree to which the research procedures adhere to professional, legal and sociological obligations to the study participants”. Bryman and Bell (2011) observe lack of informed consent and confidentiality as two ethical issues not widely debated in the academic literature. Robson (2002) emphasizes that protecting interviewees from any repercussions of their comments being reported should also be a concern for them. Creswell (2007) states that the researcher is obligated to respect the rights, needs, values and desires of the informants. Miles and Huberman (1994) provided a list of issues that researchers should be aware of before, during, and after the research is conducted. These issues include informed consent; harm and risk; honesty and trust; privacy, confidentiality, and anonymity; and intervention and advocacy. The following measures were adopted in this study to ensure that this research was conducted in an ethical manner:

a) Protection of the respondents

The researcher obtained informed consent from tea companies in Malawi. According to Polit and Beck (2010), informed consent means that participants have adequate information regarding the research, are capable of comprehending the information and have the power of free choice, enabling them to consent or decline participation in the research. In this study, the researcher informed tea companies of the nature and purpose of the study, the importance of the study and their participation, data collection methods to be applied, and the scope of the study before commencement. In line with this, a memorandum of understanding was signed between the research and tea companies.

b) Right of the participant

The study did not attempt to harm participants deliberately. In addition, those respondents who could experience any form of harm be it through victimization, emotional or otherwise, were informed in advance of their right to withdraw from participating in the study.

c) Privacy, confidentiality, and anonymity

Confidentiality means that information from participants was not going to be divulged to the public nor made available to colleagues, more specifically their competitors. Polit and Beck (2010) argues that confidentiality is maintained when participants are protected in a study such that individual identities are not linked to the information, and are never publicly divulged. They further add that anonymity occurs when even the researcher cannot link a participant with the information for that person. In this present study, the researcher himself committed to maintaining anonymity and confidentiality. All information about tea companies in Malawi was treated with utmost confidentiality and anonymity. The researcher deliberately removed any identifying characteristics before widespread dissemination of information. Participants to this study were also assured that their names would not be used for any other purposes, nor will the information revealing their identity in any way be shared.

d) Voluntary participation

In the present study, the researcher has complied with ethical procedures to protect the rights of tea companies in Malawi, involving the principle of voluntary participation that requires that participants do not need to be coerced into participating in this research. The researcher made it clear to the participants that the research was meant only for academic purposes and participation by individual tea companies was voluntary. Consequently, no company was forced to participate in this study.

5.10 Chapter summary

This chapter has described the research methodology used in this study. It reviewed the philosophical assumptions underpinning this research, and discussed the researcher’s pragmatic stance and the consequent choice of the mixed-method approach. The chapter also explained the research design adopted in this study as well as a brief description of the data collection methods, method of data analysis, and the application of data analysis. This study followed a general research process: literature review, research design, modelling, case study, validation and conclusion. A cross-sectional study design was utilised and purposive sampling was used to identify potential research participants. The procedures to carry out this PhD research are elaborated. In order to perform the modelling, case study, and validation as well as conclusion based on the findings, this study is composed of four phases, corresponding to objectives in section 1.3. The chapter concludes with a discussion of the strategies that were used to ensure that the results of this study are valid, reliable and trustworthy. The next chapter focuses on the analysis of research results and discussion of the findings.

Chapter-6
Data analysis, Results and Discussion

6.1 Introduction

The previous chapter described in detail the selection of research methodology, data collection and data analysis methods adopted for this study. This chapter presents the results obtained during the fieldwork together with their interpretation in accordance with the objectives of this study. The chapter attempts to meet the first and second objectives of this research: to identify and understand critical factors that influence sustainable productivity of tea industry in Malawi. The aim of this chapter is to report on the results of data analysis and draw conclusions from the results, which will be used as a basis for the development of a decision model for measuring and monitoring sustainable performance. The results obtained in this study will be used to guide implementation of sustainability as well as support decision-making processes in the tea industry. Therefore, it is important to understand the existing situation of the Malawian tea industry concerning sustainable productivity. This chapter consists of five sections including this introduction. The second section provides a detailed description of the methodology used in the current research. This study used the Malawian tea industry as a case study that applied a qualitative approach to answer the research question. The study used structured questionnaires and personal interviews as the main data collection methods. The third section describes findings of this exploratory study. Selection and identification of the most important indicators for the sustainability assessment of the tea industry are provided in the fourth section. The final section summarises the chapter.

6.2 Methodology

6.2.1 Research design

This study adopted an exploratory form of research design to investigate factors contributing to the decline in productivity in the Malawian tea industry, and thus affecting its performance. The second part of this study aimed at investigating the understanding and awareness of the concept of sustainability in the tea industry. Particularly, the study focused on identifying the status of sustainability practices, the awareness level and knowledge of industrial practitioners and its stakeholders, drivers that stimulate the implementation of sustainability practices, as well as potential barriers with their implementation. The productivity of the tea industry and the factors affecting the productivity as well as sustainable tea production practices are therefore of great significance to decision makers in this industry. The population of this study consists of all the tea companies operating in Malawi. The list of tea companies in the country was obtained from the Tea Association of Malawi, an umbrella body of all tea companies and stakeholders for the tea sector. There are 11 companies in Malawi and 21 operating tea-processing factories.

This exploratory study makes use of a survey research design method and primary data was collected using structured questionnaires, interviews and personal observation. The sample size for this study consists of eight tea factories. Purposeful and convenience sampling techniques were applied to select the sample from the population. Thirty-five managers (including four managing directors, two engineering directors, seven general managers, ten production managers, ten factory engineers, and two human resource managers) were involved and taken as a sample unit of study. These individuals were deemed suitable to complete the questionnaire as they had practical experience and exposure to the tea industry in Malawi. The instrument of the research adopts a 5-point Likert measurement scale ranging from "strongly disagree" to "strongly agree" and was used to measure the respondents' attitudes to the questions. The Likert scale was selected for this study, because it is commonly used (Bernard, 2000), simple to construct, permits the use of latent attitudes and it is likely to produce a highly reliable scale (Baker, 1997).

6.2.2 Data analysis

For analysing the collected data, the relative importance index was used and is calculated using the following equation (Lim & Alum, 1995):

$$RII = \frac{\sum w_i f_i}{A.N} \qquad 0 \leq RII \leq 1 \qquad (34)$$

where: *RII* denotes the relative importance index; w_i is the weight given to each factor by the respondents and ranges from 1 to 5 (where 1= strongly disagree, and 5 = strongly agree); f_i represents the frequency of response given as a percentage of total response for each factor; A is the highest weight (i.e. 5 in this case), and N is the total number of respondents.

6.3 Results and discussions

6.3.1 Awareness and understanding of productivity

This section presents the results of tea managers' awareness and understanding of productivity. It further focuses on tea managers' familiarity and understanding of the term productivity. In order to gain an insight into the level of awareness and knowledge among tea industry managers with regard to the concept of productivity, the participants were asked to indicate their familiarity with the term productivity. Figure 6.1 demonstrates that 75% of the managers understand productivity as outputs per materials input, while 25% strongly agreed. Furthermore, 75% of the respondents also defined productivity as being output per energy input. However, 13% of the respondents disagreed on the application of this definition. Similarly, 88% of the respondents agree with the definition of productivity as output per man-hours. Results also show that defining productivity as output per machine-hour received the least approval, with 38% agreeing with the definition, 13% disagreeing while 25% strongly agreeing.

Respondents were also asked to tell how they define productivity in their own sphere of authority. The more appropriate definitions applicable to the tea industry are displayed in Figure 6.2. The study reveals that there is an opinion within the tea industry that productivity means obtaining more output for the same input. Consequently, productivity is best described by the respondents as the ratio of made tea output per hectare; yield of green leaf per hectare; and made tea quantity per quantity of green leaf processed, which are similar to the above global definitions. These findings are consistent with those of De Costa *et al.* (2007), who observe that the productivity of tea should be estimated based on the weight of made tea per unit land area per year.

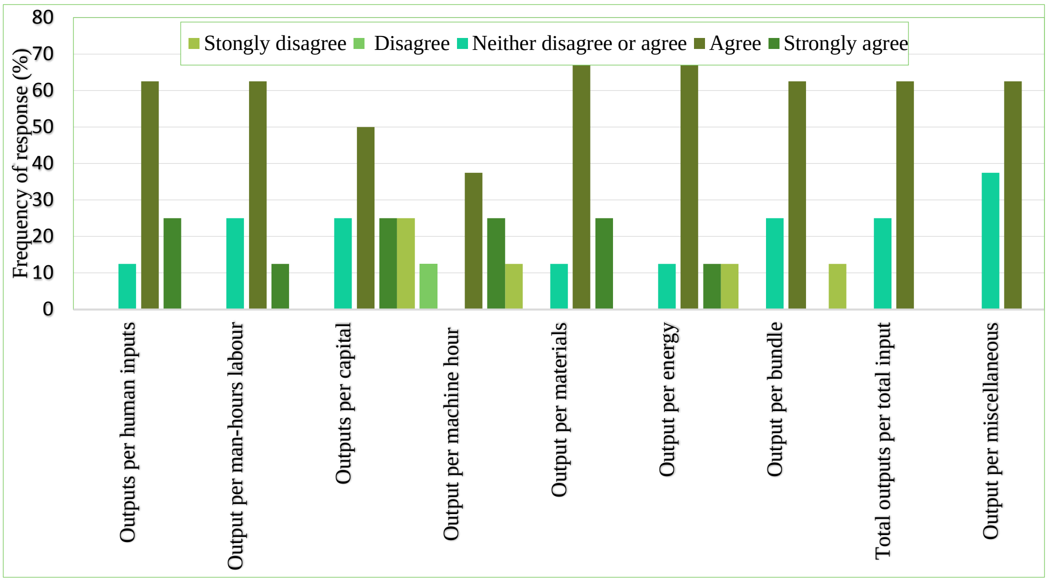

Figure 6.1: Defining productivity in tea industry

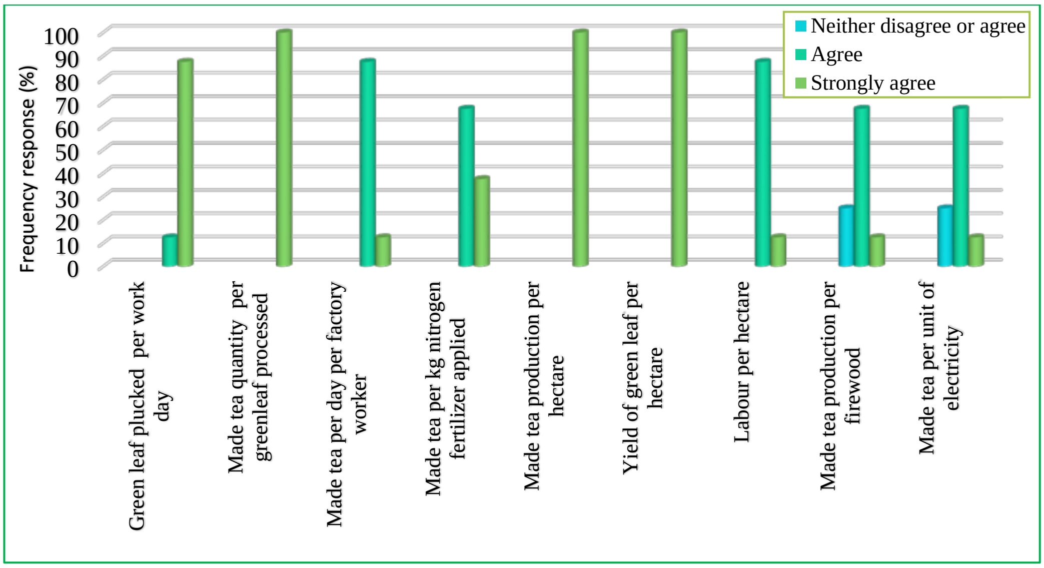

Figure 6.2: Defining productivity in the context of the tea industry

6.3.2 Factors influencing productivity in the tea industry

In this study, 44 factors negatively affecting productivity in the tea industry in Malawi have been identified and ranked according to their relative importance index by Microsoft Excel spreadsheet. These factors have been classified into seven groups: human, capital, material, method, control, process, and product factors. Table 6.1 summarizes the computed average relative importance index of group factors and their ranks as perceived by the surveyed tea companies in Malawi. The results of this study revealed that material factors are the most important of all the factors negatively affecting productivity of tea manufacturing in Malawi. Material factors were ranked in the first position of all seven group of factors negatively affecting manufacturing productivity.

The result is supported by findings of the FAO study, which observed that the concentration of the majority of overall production in just a few months has a negative impact on the productivity of the tea sector as well as the quality of the tea produced. Approximately 80% of tea production is concentrated in the rainy season (December to April), with the remainder in dry season (May to November), forcing factories to shut down or run at reduced capacity due to shortage (non-availability) of green leaf. On the other hand, product factors group was ranked the least important among all factors groups.

Table 6.1: Group of factors affecting productivity of tea manufacturing

Factor group	RII	Rank
Human	0.50	3
Capital	0.47	4
Materials	0.71	1
Methods	0.42	5
Control	0.41	6
Process	0.55	2
Product	0.38	7

(1) Human factors

Table 6.2 shows the relative importance index and ranking of the nine factors for the human factor group. The results show that the most important factor negatively affecting the productivity of tea manufacturing is motivation and morale, followed by attitude and culture, human hour utilization, human capacity, life standard, absenteeism, turnover, employee satisfaction, and knowledge and skill. The surveyed tea managers ranked motivation and morale in the first position, with an important index value of 0.68. This factor was also ranked second position among all 44 factors, affecting the productivity of the tea manufacturing industry in Malawi (Table 6.9), which indicates that employee motivation and morale has a great influence on productivity. This is supported by Neely (1999), who argues that motivation and morale have a detrimental effect on an organization's productivity. Clearly motivation leads to productivity and the reverse is true that productivity leads to motivation. Attitude and culture had a great effect on productivity, and was ranked in the second position in the human factors group, with an importance of 0.53, and ranked ninth among all 44 factors affecting productivity (Table 6.9). Findings also show that tea managers rated “knowledge and skill”, resulting from training and experience, as having a low effect on productivity, with this factor being ranked at position 39 of all 44 factors affecting productivity.

Table 6.2: Ranking factors under human group

Factor	RII	Rank
Knowledge and skill	0.38	9
Motivation and morale	0.68	1
Employee satisfaction	0.43	8
Attitude and culture	0.53	2
Life standard	0.50	5
Absenteeism	0.48	6
Turnover	0.48	7
Human hour utilization	0.53	3
Human capacity	0.53	4

(2) Capital factors

The relative importance index and the rank of capital factors are summarized in Table 6.3. Results showed that the most important factor affecting productivity of tea manufacturing was maintenance, followed by depreciation, technological capacity, speed loss, machine hour utilization, inventory, technical capacity, and process capacity. Maintenance was ranked first in the capital factors group, and was ninth among all 44 factors affecting productivity of tea manufacturing (Table 6.9). This is not surprising considering the key roles maintenance plays in keeping and improving availability, performance efficiency, quality products, environment and safety requirements, and total plant costs effective at high levels (McKone & Elliot, 1998). The improved availability of plants through proper maintenance and reduction of idle time increased production.

To increase productivity, managers in this industry need to pay proper attention to utilization, age, modernization, cost, and investment. This result is also supported by Alsyouf (2007), who stated that an effective maintenance policy influences the productivity of a manufacturing process. He further observes that any disturbances in the production process due to maintenance reduce productivity, increase production costs and thereby reduce profitability. Results also show that technological capacity has a high effect on productivity of tea manufacturing, and ranked 12th among all factors negatively affecting productivity. This result is not surprising, because technology plays a prominent role in enhancing productivity. Although processing techniques for tea manufacturing have greatly improved over the decades, the Malawian tea industry has been relatively slow in implementing new technologies compared to similar industries in the region or elsewhere. The improvements because of technological progress have not been noticeable over a short period. Managers also rated “process capacity” as having low impact on manufacturing productivity.

Table 6.3: Ranking factors under capital group

Factor	RII	Rank
Technical capacity	0.43	7
Technological capacity	0.51	3
Process capacity	0.40	8
Maintenance	0.53	1
Depreciation	0.53	2
Speed loss	0.48	4
Machine hour utilization	0.48	5
Inventory	0.45	6

(3) Material factors

Table 6.4 shows the ranking of the two factors under material group. These were ranked according to their importance in affecting the productivity of tea manufacturing as follows: material shortages; and material quality. The analysis shows that materials shortage is the most important of all factors negatively affecting productivity of tea manufacturing. Material shortage was ranked in the first position of all 44 factors negatively affecting productivity, a clear indication that production cannot be accomplished without the requisite materials. Material quality is ranked second in this group, with a relative importance index of 0.50 and tenth among the 44 factors (Table 6.9). Poor quality of materials increases production costs through reprocessing and lowers productivity of a production system.

Table 6.4: Ranking factors under material group

Factor	RII	Rank
Material quality	0.50	2
Shortage	0.92	1

(4) Method factors

Table 6.5 indicates the ranking of seven factors under the group related to methods. The results show that the most important factor affecting manufacturing productivity in the tea industry is work study, followed by procedures, incentive schemes, ergonomics, quality control, work formats, and rules and regulations. The surveyed tea companies ranked “work study” in the first position, with an importance index value of 0.50. This factor was also ranked in the ninth position among all 44 factors, negatively affecting manufacturing productivity in the tea industry. This result is supported by Duran *et al.* (2015), who found that lack of work study leads to wasteful use of resources and consequently increases production costs. Work study aims at examining the way an activity is being carried out, simplifying or modifying the method of operations to reduce unnecessary or excess work, or the wasteful use of resources and setting up a time standard for performing that activity. The core objective of work study is to identify and eliminate unnecessary activities. This is further corroborated by Kanawaty (1992), who showed that work study is positively correlated with productivity. Work procedures were ranked in the second position in the methods group, with an importance index of 0.48. It was also ranked eleventh among all 44 factors negatively affecting productivity of tea manufacturing (Table 6.9).

Table 6.5: Ranking factors under methods group

Factor	RII	Rank
Rules and regulations	0.35	7
Procedures	0.48	2
Work formats	0.38	6
Incentive schemes	0.43	3
Ergonomics	0.43	4
Work study	0.50	1
Quality control	0.40	5

(5) Control factors

Table 6.6 presents the ranking of seven factors under the control group. These factors were ranked according to their importance in affecting the productivity of tea manufacturing as follows: rejection, quality control, environmental control, inventory control, production control, and process control. Results demonstrate that rejection has a high impact on productivity of manufacturing, with a relative importance index of 0.60, hence being ranked in the sixth out of all the 44 factors negatively affecting productivity of manufacturing in the Malawian tea industry. The study finds that rejection affects the cost of the product. The higher the rate of rejection, the greater is the cost of production. This signifies poor and inefficient working of the manufacturing process, which means low productivity. Results further show that quality control affects the productivity of tea manufacturing, with a relative importance of 0.40. Poor quality of finished product results in lower productivity, loss of productive time, loss of material, and even loss of business.

Table 6.6: Ranking of factors under control group

Factor	RII	Rank
Quality control	0.40	2
Inventory control	0.38	4
Production control	0.35	5
Process control	0.35	6
Environmental	0.40	3
Rejection	0.60	1

(6) Process factors

The relative importance index and rank of process factors are summarized in Table 6-7. The study found that lead-time has a high impact on the productivity of manufacturing followed by waiting time, transfer time, setup time, work in progress, rejection, internal transport, standard time, downtime, rework, and scrap. Results demonstrate that lead-time has a high impact on productivity of manufacturing, with a relative importance index of 0.65, and being ranked in the sixth position of all 44 factors negatively affecting productivity of manufacturing in the Malawian tea industry. This factor is the most important one for the Malawian tea industry because of total reliance on the foreign markets. Long lead-times are still a major obstacle that negatively affects the performance of the tea industry.

The survey established that delivery of tea to European markets takes almost three months, compared to three weeks for Kenya's tea, placing the latter in a more competitive position than others. Lysons and Farrington (2012) asserted that reducing delivery lead-times could improve competitive advantages, offer significant shorter and more reliable service delivery time, and boost its corporate image in the face of partners and stakeholders.

Table 6.7: Ranking factors under process group

Factor	RII	Rank
Rejection level	0.60	6
Rework	0.43	10
Scrap	0.40	11
Work in progress	0.63	5
Standard time	0.50	8
Lead-time	0.65	1
Waiting time	0.63	2
Transfer time	0.63	3
Downtime	0.45	9
Setup time	0.63	4
Internal transport	0.53	7

(7) Product factors

The relative importance index and ranking of product factors are summarized in Table 6.8. Results indicate that main grade percentage plays an important role in determining the productivity of tea industry, with a relative importance index of 0.40, and being ranked in first place in the product group. This factor is an important one for tea industry managers because it reflects the quality and maintenance of machinery used in the production system. Factory machines should be run at optimum conditions to manufacture high quality standards, which also relates to profitability and productivity. Increased percentage of main grade signifies improved quality and maintenance of machinery, which in turn, fetches higher prices at the auction markets, while secondary (refuse) tea which reflects the quality of raw materials (green leaf), is a by-product originated in the manufacturing process. This result is supported by Baruah and Bhattacharya (1996) who stressed the need to improve the quality of tea machinery so as to enhance factory efficiency and productivity.

Table 6.8: Ranking factors under in the product group

Factor	RII	Rank
Product quality	0.35	2
Main grade percentage	0.40	1

Table 6.9: Overall ranking of factors affecting productivity in Malawi

Factor	RII	Rank
Knowledge and skills	0.38	39
Motivation and morale	0.68	2
Employee satisfaction	0.43	29
Attitude and culture	0.53	10
Life standard	0.50	17
Absenteeism	0.48	21
Turnover	0.48	21
Human hour utilization	0.54	10
Human capacity	0.53	10
Technical capacity	0.43	29
Technological capacity	0.51	16
Process capacity	0.40	33
Maintenance	0.53	10
Depreciation	0.53	10
Speed loss	0.48	21
Machine hour utilization	0.48	21
Inventory	0.45	26
Material quality	0.50	17
Shortage	0.92	1
Rules and regulations	0.35	42
Procedures	0.48	21

Factor	RII	Rank
Work formats	0.38	39
Incentive schemes	0.43	29
Ergonomics	0.43	29
Work study	0.50	17
Quality control	0.40	33
Quality control	0.40	33
Inventory control	0.38	39
Production control	0.35	42
Process control	0.35	42
Environmental	0.40	33
Rejection	0.60	8
Rejection	0.60	8
Rework	0.43	28
Scrap	0.40	33
Work in progress	0.63	4
Standard time	0.50	17
Lead-time	0.65	3
Waiting time	0.63	4
Transfer time	0.63	4
Downtime	0.45	26
Setup time	0.63	4
Internal transport	0.53	10
Made tea quality	0.35	42
Main grade percentage	0.40	33

6.3.3 Awareness and understanding of sustainability

To find stakeholder understanding of the term, the questionnaire included a section on defining sustainability. The responses to this question were based on a 5-point Likert type scale ranging from “very poor” to “excellent.” The results of the survey indicate that the majority of managers in the tea industry in Malawi were aware and had practical knowledge of sustainability principles. The surveyed company managers agreed that the level of application of sustainability principle were either moderate or good level, as shown in Table 6.5. The study found that 19% of the managers believe that they have moderate knowledge about sustainability, with 45% considered to have good knowledge, whereas 30% consider themselves excellent and 13% considered their knowledge of the sustainability concept to be low. The study did not find that any manager had poor knowledge of the sustainability concept – a clear indication that awareness of the concept of sustainability does exist in the tea industry.

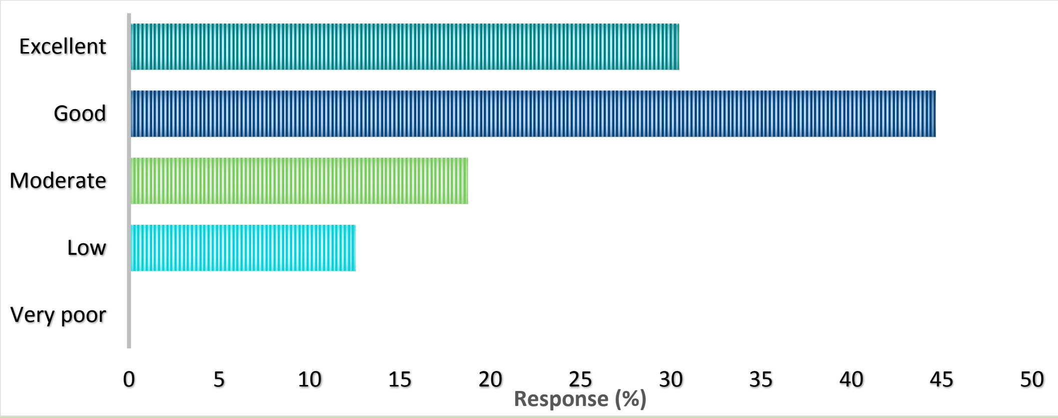

Figure 6.3: Knowledge of sustainability concept in the tea industry in Malawi

6.3.4 Sustainability reporting adoption

The respondents were asked to evaluate each of the 10 presented statements, being reasons for not adopting sustainability in the tea industry. The results are displayed in Table 6.5. The majority (88%) of the respondents believe sustainability concepts and principles are relevant to the tea manufacturing industry, with 50% of them disagreeing that social and environmental issues are not relevant, while 37.5% strongly disagreed. The survey also found that 37.5% of the respondents strongly disagreed that the cost required to report on sustainability issues outweigh the benefits while 25% were neutral. Furthermore, 50% disagreed that their stakeholders do not require sustainability reporting, while 12.5 % think the current guidelines for sustainability reporting are too onerous. About 75% of the respondents disagreed with the notion for voluntary reporting of sustainability, with 62.5% disagreeing that the current sustainability reporting practices and guidelines are too vague. Findings also suggest that only 12.5% of the respondents agreed that information on their organization’s sustainability performance is unavailable. Notably, 62.5% disagree that reporting is too qualitative and hard to verify, and therefore, lacks credibility, while 75% disagree that their stakeholders are already overloaded with information provided in other external reports.

6.3.5 Perceptions on adoption of sustainability practices

Table 6.10 shows the relative importance indices and the ranking of reasons for adopting sustainability in the tea industry. The majority of the respondents reported that pressure from customers is the main reason for the adoption of sustainability practices in the tea industry, followed by globalization and international pressures, compliance with environmental rules and regulations, pressure from competition, employee pressure, and a desire to be a leader for sustainability. Moreover, 63% of the participants strongly agreed that pressure from customers as being the main reason driving sustainability in the Malawian tea industry. This is corroborated by Porter and Van der Linde (1995) who posited that consumers and importers consider as unique or innovative those products that are sustainably produced and environmentally benign. They further demand that the tea supply chain complies with employee social and welfare standards. Furthermore, nearly 38% agreed on globalization and international pressures as reasons for adopting sustainability practices.

Table 6.10: Reasons for adopting sustainability practices

Reason	RII	Rank
To comply with environmental rules and regulations	0.63	3
Voluntarily (desire to be a leader for sustainability)	0.58	6
Under pressure from employees	0.58	5
Under pressure from customers	0.73	1
Globalization and international pressures	0.70	2
Under pressure from competition	0.58	4
Other	0.40	7

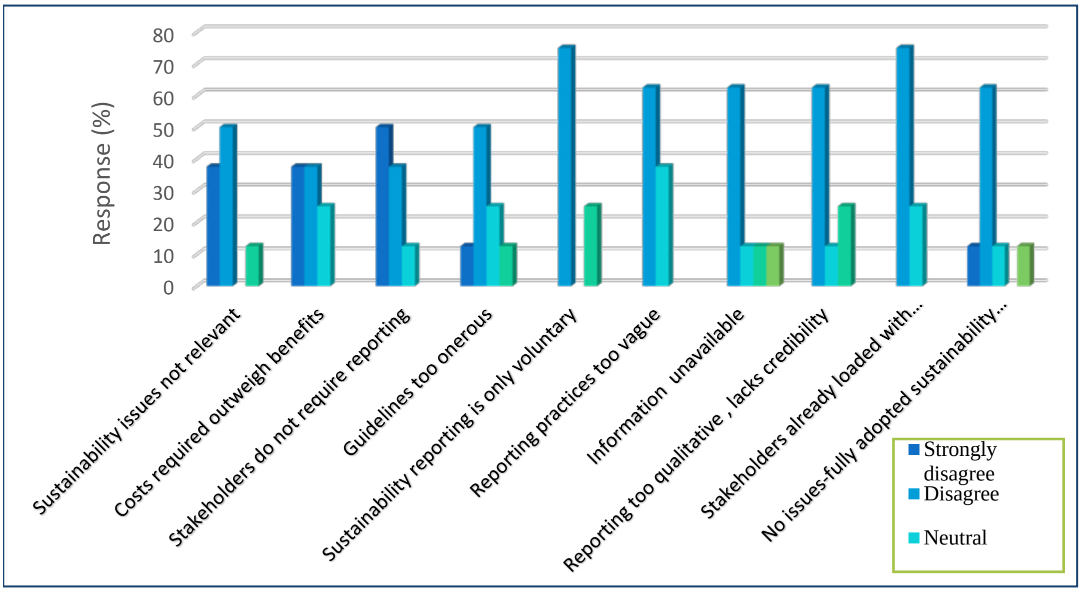

Figure 6.4: Reasons for not adopting sustainability reporting

6.3.6 Perceived benefits of adopting sustainability practices

To find the perceived benefits the study's questionnaire included a section about the "benefits of sustainable production practices in the tea industry." Table 6-11 shows the relative importance and ranking of perceived benefits for tea companies who adopted sustainability practices. Results indicate that the majority (66%) of the respondents were of the opinion that sustainable production practices result in cost savings in production. Managers in the surveyed companies reported that improvement in product and process quality, and improvement in efficiency and productivity were the most positive benefits. Other benefits that drive the tea industry to adopt and implement sustainable production practices include: increase in sales of product, increase in market share, penetration of new markets, acquisition of new customers, and increase in organizational growth. Compared to other benefits, enhancement of corporate image and influencing policy makers and regulators received the least agreement.

Table 6.11: Perceived benefits of sustainability practices

Benefits	RII	Rank
Improvement in product and process quality	0.7	1
Improvement in efficiency and productivity	0.7	1
Innovation in product and process design	0.7	1
Cost savings in production	0.68	2
Increase in sales of products	0.7	1
Increase in market share	0.68	2
Penetration of new markets	0.68	2
Acquisition of new customers	0.68	2
Increase in organizational growth	0.7	1
Enhancement of corporate image	0.65	3
Achieving first-mover advantage	0.7	1
Reaping long-term advantage	0.7	1
Patenting of products and processes	0.68	2
Influencing policy makers and regulators	0.63	4
Other	0.2	5

6.4 Proposed framework for sustainable performance assessment

There is a lack of comprehensive management framework for integrated sustainability assessment of the tea industry (Singh *et al.*, 2009). In addition, there has been little research into identifying the criteria and prioritizing and ranking the alternatives to develop a sustainability assessment framework for the tea industry supply chain for Malawian companies. Thus, the challenge for the tea industry's efforts towards sustainable production is to use appropriate methods and measures to solve their specific sustainability problems. Selection of appropriate performance indicators and the implementation of an effective sustainability performance system are needed (Staniskis & Arbaciauskas, 2009a) in order to manage integration of tools and to ensure effective information flow for decision-making.

This section presents a framework for integrated sustainability performance assessment for a firm or industrial level tea supply chain. The framework proposed in this study is based on the work of Krajnc and Glavic (2005) and aims to assess and improve the sustainability of the tea industry in Malawi. It consists of a set of seven steps and uses the AHP to determine the sustainability weights for the performance criteria, and simple additive weighting (SAW) method is applied to aggregate economic, environmental and social indicators into a composite sustainability performance index for the tea industry. The proposed framework represents a contribution in the area of index construction and a valuable component of organizational management systems and monitoring programs, serving as a benchmarking tool for managers to evaluate the sustainability behaviour of their own supply chain and compare it with their peers in the similar industry, and to improve the dimension of sustainability in which they perform worst. Figure 6.5 illustrates the framework. The hierarchy structure adopted for this study is depicted in Figure 6.6. The step-wise methodology for the development of the composite sustainability index for the tea industry comprises the following steps:

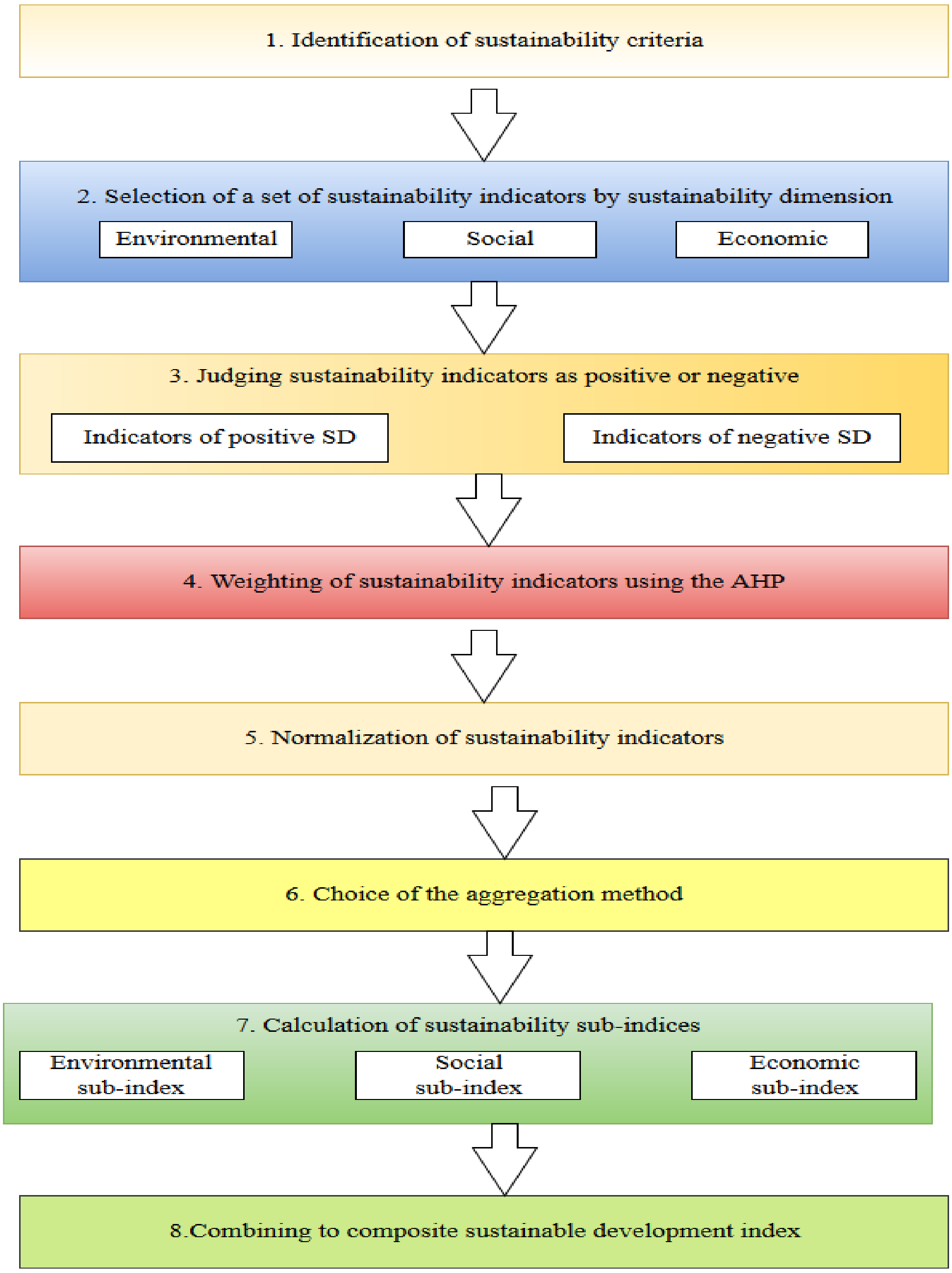

Figure 6.5: An integrated framework for the assessment of sustainability index

6.4.1 Selection of sustainability indicators

This section aims to identify and select indicators that can be used to measure the sustainability of the Malawian tea industry. To make sustainability performance evaluation meaningful in terms of better enterprise management, there is a need for development of the tea industry-specific indicators (Labuschagne *et al.*, 2005). According to Azapagic (2003) and Singh *et al*. (2007), the set of indicators can be identified in a number of ways, including theory findings, empirical analysis, and consultation with stakeholders, among others. In this study, the researcher has adopted the indicators set provided by Joung *et al.* (2013). The set of indicators were chosen for three reasons: (i) it is a combination of 11 established indicator sets published by recognized international bodies, manufacturing leaders, research and private institutions, (ii) the sustainable manufacturing process developed by Joung *et al.* (2013) is hierarchal which provides groupings of indicators into subcategories, subcategories into categories, and categories into sustainable manufacturing dimensions, and (iii) it is the most comprehensive indicator set recently developed. A summary of indicators adopted for this study is given in Appendix A.

6.4.2 Judging sustainability indicators as positive or negative

Experienced managers in the tea industry judge the applied indicators for this study from a sustainability view. According to Krajnc and Glavic (2005), the positive indicators are those whose increasing value have a positive impact on sustainable development and indicators of negative performance have the adverse impact on sustainable development. For example, increased value of air emissions per unit of tea production clearly has a negative impact, while increased operating profit is a value with a positive impact to the economic performance of the industry.

6.4.3 Weighting the indicators using AHP method

To specify the selected set of indicators for sustainability assessment in the Malawian tea industry, a two-stage Delphi process was adopted. A purposive sampling approach was used to select a group of experts. The criteria used to select these experts included (i) those having knowledge and understanding of sustainability and sustainable development issues, and (ii) those with practical experience working in the tea industry as well as those involved in the industry's research topics. The researcher invited five experts to fill out the structured questionnaire. The chosen experts were predominantly tea managers, since they were considered to be a major target group as future users of the developed model. The first round of Delphi questionnaire was delivered by hand to the group of panel members at the end of February 2014. The results of this round were consolidated and presented to the panel members. Furthermore, the panel members were requested to reconsider whether they would like to change any of their original choices in the light of the consolidated results from the first round. All five questionnaires were completed at the end of December 2015.

To determine the weights of indicators, the AHP technique was used. The AHP as a method widely applied by researchers was employed for the sustainability assessment of the tea industry in Malawi for the following reasons: (1) it does not require weights directly assigned to each criterium, all comparisons are made in pairs. The criteria shown in the subsequent tables cannot be directly aggregated since they are measured in different units. The AHP can be used to resolve this problem because it allows for the data to be normalized and subsequently aggregated; (2) it can detect inconsistent judgements and provide an estimate of the degree of inconsistency in the judgement; and (3) the multidimensional nature of the method allows the researcher to tackle qualitative problems. The details of this method can be found in a study by (Saaty, 2001). Using Saaty's fundamental 9 point scale, pairwise comparisons were performed on sustainable production dimensions, criteria and sub-criteria. There were 33 pairwise comparisons to be determined by the experts in the questionnaire. Using the eigenvector method proposed by Saaty (2001), respective weights for each of the elements were computed.

The matrix of pairwise comparisons of economic, social, and environmental criteria to the final sustainability goal based on stakeholder's opinions and decision-makers' judgments is shown in Table 6.12, along with the resulting vector of priorities. Experts ascribed the greatest importance to the economic growth, whose weight is 0.5012. The social well-being goal of sustainability scored 0.3803, and the environmental aspects 0.1185. The largest eigenvalue λ_{max} of the 3 factor matrix is 3.1651 as provided in Table 6.12, and therefore the calculated consistency index is equal to 0.0826. Clearly, as stated before, a *CI* ratio that is less than 10% (0.1) is acceptable and the judgments are said to be consistent.

Table 6.13 to Table 6.15show the pairwise comparison matrix for the economic and environmental criteria as well as pollution category, as given by the decision makers in tea industry. For the economic criteria, the highest local priority was given to net present value (0.5115) followed by total annualized costs (0.2433) and operating costs (0.1466), and the lowest weight in the category was scored by discounted cash flow rate of return (0.0986). The maximum eigenvalue was 4.0476, which resulted in a CI value of 0.0159. The calculated consistency ratio (CR) was 0.0176 and was found to be acceptable and the judgments were undoubtedly consistent.

With regard to the environmental aspect, the highest local priority was given to pollution (0.3704) followed by emissions (0.2795) and resource consumption (0.1790), and natural habitat conservation scored the lowest weight in the category. The maximum eigenvalue was determined at 4.1911, which resulted in a CI value of 0.0637. The calculated consistency ratio (CR) was 0.0708 and was found to be acceptable and the judgments were undoubtedly consistent.

For the pollution aspect, the highest local priority was given to toxic substances (0.4972) followed by greenhouse gas emissions (0.2486), ozone depletion gas emissions (0.0994) and noise (0.0994), and the lowest weight in this category was scored by acidification (0.0552). In the social criteria, the greatest local priority was given to human rights (0.4972) followed by working conditions (0.2486), cultural heritage (0.0994) and social-economic repercussions (0.0994), and governance scored the lowest weight in this category.

For both pollution and social criteria, the maximum eigenvalue was 5.000, which resulted in a CI value of 0.0000. The calculated consistency ratio (CR) was calculated as 0.0000, and was found to be acceptable and the judgments were undoubtedly consistent. According to Saaty (1990), a CR of 0.000 indicates perfect consistency while that of 0.1000 means no consistency in a matrix. Inconsistency is expected to occur due to the careless errors or exaggerated judgements of the respondents during the process of pair-wise comparison. The final results of parameter weights allocation using the AHP method are shown in Table 6.17. Results show that for the respondents, the most important aspect of sustainable tea production is concentrated in economic growth and social well-being dimensions. This is an indication that socio-economic issues are highly relevant in sustainable production. Findings of the study confirm profit maximization as being the principal objective of a business firm, whose weight was the highest (0.5013). Managers in the tea industry should pay more attention in increasing revenue generation, capital investment as well as reducing production costs.

Environmental stewardship elements were given low priority weighting (0.1185), suggesting that respondents recognize that the natural environment in Malawi is not under significant threat from the current tea production practices. This result is not surprising since environmental repercussions of tea growing are underestimated, save for its contribution to deforestation when clearing virgin land for new plantation. However, emerging evidence seems to suggest that tea growing activities raise various environmental impacts and that more studies are needed to increase our understanding of these impacts. Concerning the social criteria, there is a need to focus on the improvement of human rights of tea industry employees. Human rights violations have been reported at plantations in virtually all major tea producing countries including Malawi. The benefits paid to employees, wages and salaries as well as the issues of child labour should be key concerns for tea management.

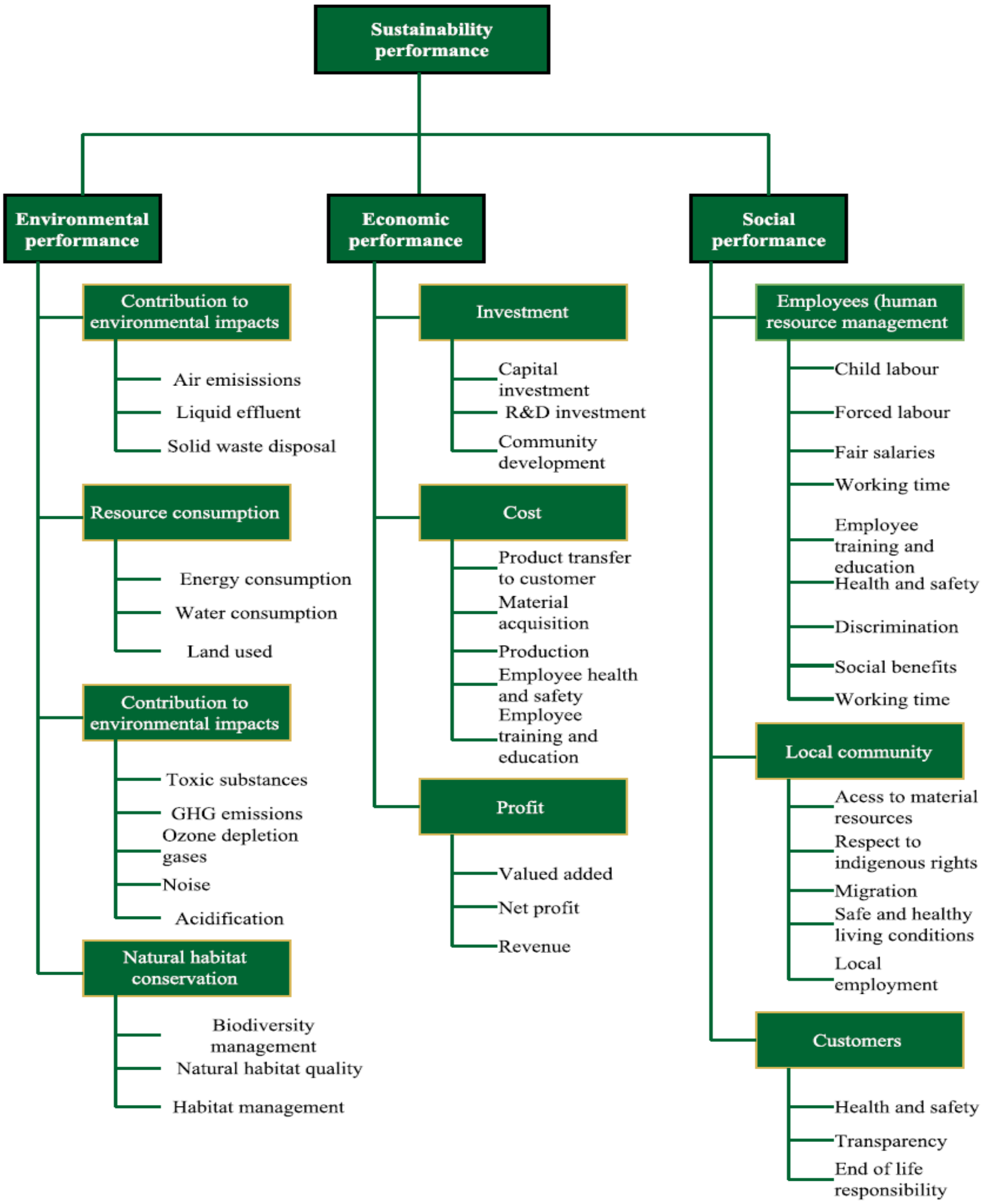

Figure 6.6: Hierarchical structure of sustainable performances based on TBL approach

Table 6.12: Pairwise comparison table for main sustainability components

	Environmental	Social	Economic	Priority vector
Environmental	1	1/5	1/3	0.1185
Social	5	1	1/2	0.3803
Economic	3	2	1	0.5012

CI = 0.0826 *CR* = 0.1424 λ_{max}= 3.1651

Table 6.13: Pairwise comparison matrix for economic criteria

	NPV	IRR	TAC	TOC	Priority vector
NPV	1	5	2	4	0.5115
DCFROR	1/5	1	1/2	1/2	0.0986
TAC	1/2	2	1	2	0.2433
TOC	1/4	2	1/2	1	0.1466

CI = 0.0159   *CR* = 0.0176 λ_{max}= 4.0476

Table 6.14: Pairwise comparison matrix for environmental criteria

	Pollution	Emissions	Resource consumption	Natural habitat conservation	Priority vector
Pollution	1	1	3	2	0.3704
Emissions	1	1	1	2	0.2795
Resource consumption	1/3	1	1	1	0.1790
Natural habitat conservation	1/2	1	0.5	1	0.1710

CI = 0.0637   *CR* = 0.0708 λ_{max}= 4.1911

Table 6.15: Pairwise comparison matrix for pollution

	Toxic Substances	GHG Emissions	Ozone depletion	Noise	Acidification	Priority vector
Toxic substances	1	2	5	5	9	0.4972
GHG emissions	1/2	1	2 1/2	2 1/2	4 1/2	0.2486
Ozone depletion	1/5	2/5	1	1	1 4/5	0.0994
Noise	1/5	2/5	1	1	1 4/5	0.0994
Acidification	1/9	2/9	5/9	5/9	1	0.0552

CI = 0.0000   *CR* = 0.0000 λ_{max}= 5.000

Table 6.16: Pairwise comparison matrix for the social criteria

	Human rights	Working conditions	Cultural heritage	Social-economic repercussions	Governance	Priority vector
Human rights	1	2	5	5	9	0.4972
Working conditions	1/2	1	2 1/2	2 1/2	4 1/2	0.2486
Cultural heritage	1/5	2/5	1	1	1 4/5	0.0994
Social-economic repercussions	1/5	2/5	1	1	1 4/5	0.0994
Governance	1/9	2/9	5/9	5/9	1	0.0552

CI = 0.0000   *CR* = 0.0000 λ_{max}= 5.000

Table 6.17: Weight allocation using AHP

Elements		Priority weight		
1. Environmental stewardship				0.1185
Pollution			0.3704	
	Toxic substances	0.4972		
	Greenhouse gas emissions	0.2486		
	Ozone depletion gas emissions	0.0994		
	Noise	0.0994		
	Acidification	0.0552		
Emissions			0.2795	
	Effluent	0.4954		
	Air emissions	0.1001		
	Solid emissions	0.1920		
	Waste energy emissions	0.2125		
Resource consumption			0.1790	
	Water consumption	0.0899		
	Material use	0.1803		
	Energy consumption	0.2811		
	Land use	0.4486		
Natural habitat conservation			0.1710	
	Biodiversity management	0.5714		
	Natural habitat quality	0.2857		
	Habitat management	0.1429		
2. Economic growth				0.5012
Investment			0.1185	
	Capital investment	0.5485		
	Research and development investment	0.2106		
	Community development	0.2409		
Cost			0.3803	
	Product transfer to customer	0.1593		
	Material acquisition	0.2519		
	Production	0.5889		
Profit			0.5013	
	Value added	0.1185		
	Net profit	0.3803		
	Revenue	0.5013		
3. Social well-being				0.3803
Employees			0.5714	
	Child labour	0.1748		
	Forced labour	0.0662		
	Fair salary	0.1783		
	Working time	0.0193		
	Discrimination	0.0356		
	Health and safety	0.0449		

	Social benefits	0.1798	
	Freedom of association and collective bargaining	0.3011	
Local community			0.1429
	Access to material resources	0.3061	
	Respect to indigenous rights	0.3050	
	Safe and healthy living conditions	0.1708	
	Local employment	0.1222	
	Migration	0.0959	
Customers			0.2857
	Health and safety	0.6000	
	Transparency	0.2000	
	End of life responsibility	0.2000	

6.4.4 Normalization of the sustainability indicators

The indicators chosen were both qualitative and quantitative over widely differing ranges. Normalization involved the conversion of these indicators and/or variables to a comparable form, ensuring the commensurability of data. To compute the composite sustainable performance index for the tea industry, the collected values of the sustainability indicators were normalized using the Min-Max (Kinderyte, 2008; Krajnc & Glavic, 2005) methods expressed as follows:

$$I_{N,ijt}^{+} = \frac{I_{A,ijt}^{+} - I_{min,jt}^{+}}{I_{max,jt}^{+} - I_{min,jt}^{+}} \tag{35}$$

$$I_{N,ijt}^{-} = \frac{I_{A,ijt}^{-} - I_{min,jt}^{-}}{I_{max,jt}^{-} - I_{min,jt}^{-}} \tag{36}$$

where $I_{A,ijt}^{+}$ / $I_{A,ijt}^{-}$ denotes an indicator of which the increasing value has a positive or negative impact on sustainability. $I_{min,jt}^{+}$/ $I_{min,jt}^{-}$ represents an indicator with minimum value and positive/negative impact on sustainability; $I_{max,jt}^{+}$/$I_{max,jt}^{-}$ is an indicator with maximum value and positive/negative impact on sustainability; $I_{N,ijt}^{+}$/ $I_{N,ijt}^{-}$ denotes the normalized indicator of which the increasing value has a positive/negative impact on sustainability; i = sustainable development indicator, j = group of sustainable development indicators: manufacturing processes; t= time in years.

6.4.5 Computation of sub-indices by sustainability dimension

To assess the sustainability of the industry, the sustainability sub-indices are calculated based on the method of Krajnc and Glavic (2005). According to this method, the normalized value for each indicator in the aggregated matrix is multiplied by the related priority weight. The sum of the result is the sustainability performance sub-indices, which signifies the importance of the economic, environmental and social performance in the sustainability of the tea industry.

$$I_{S,jt} = \sum_{jit}^{n} W_{ji} I_{N,ijt}{}^{+} + \sum_{jit}^{n} W_{ji} I_{N,ijt}{}^{-} \tag{37}$$

$$\sum_{jt}^{n} W_{ji} = 1 \;, \qquad W_{ji} \geq 0 \tag{38}$$

where $I_{S,jt}$ is the sustainability sub-index for a group of indicators j in year t, W_{ji} is the weight of indicator i for the group of sustainability indicators j and reflects the preference of this indicator in the sustainability assessment of the company.

6.4.6 Computation of composite sustainability index for tea production (C_{SUIT})

Finally, the calculated sustainability sub-indices were combined into an integrated index for the assessment of the overall composite sustainability performance of the industry, C_{SUIT}, using the following equation.

$$C_{SUIT,t} = \sum_{jt}^{n} W_j \, I_{S,jt} \tag{39}$$

where W_j denotes the weight given to the group j of sustainable indicators (as criteria) and $I_{S,jt}$ is the sustainability sub-index for a group of indicators j in year t, and $C_{SUIT,t}$ is the composite sustainability index.

6.4.7 Interpretation of results and determination of overall sustainability of tea industry

To be able to interpret the results and for decision-making purposes, this study adopted values proposed by Krajnc and Glavic (2005). For composite index with a value lower than 0.33, the company is deemed unsustainable; between 0.33 and 0.66, the industry shows the average level of sustainability. For $I_{CSD,t}$ value exceeding 0.66, it can be stated that the industry is on the right path to become comprehensively sustainable. Figure 6.6 presents the computation of sub-indices and the composite sustainability performance index for the Malawian tea industry. The quantitative sub-indices are economic (0.2744), environmental (0.0632), and social (0.1619). The calculated composite sustainability performance index of the tea industry is 0.4995, indicating a medium level of sustainability. The environmental sub-index of sustainability is the one that presented the lowest values, highlighting opportunities for improvement.

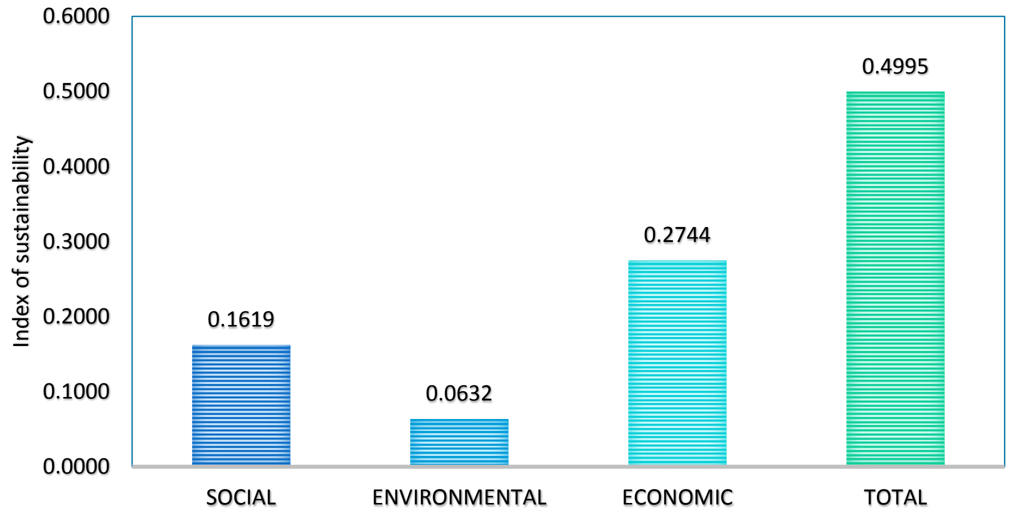

Figure 6.7: Index of sustainability for the Malawian tea industry

6.5 Chapter summary

This chapter has presented the qualitative and quantitative research results of this study. This exploratory part of the study aimed to identify the status of sustainability practices, the awareness level and knowledge of tea industry practitioners and its stakeholders, drivers that stimulate implementation of sustainability practices. This study also investigated factors that affect the productivity of the tea manufacturing in Malawi negatively. Findings of this study have thrown valuable light on the knowledge and awareness on the concept of productivity and sustainability in the tea industry. It was very clear from the survey that there is an opinion within the tea industry that tea managers have no objections in defining productivity as obtaining more output from the same input. However, there are observations and concerns that productivity in the tea industry should be defined with respect to the use of land and labour. Consequently, an appropriate definition of productivity should be made for tea output per ha, workday, green leaf processed, kilogram of nitrogen fertilizer applied.

The study identified factors that affect the productivity of the tea industry in Malawi negatively. These can be classified in seven groups: human, capital, material, method, control, process, and product factors. Material factors were ranked in the first position of all seven group factors that affect the productivity of the tea industry negatively. Lack of or shortage of materials force factories to either shut down for a considerable number of months or run at reduced capacity. The quality of materials (green leaf) alongside maintenance of tea factory machinery affects the main grade percentage, which in turn, fetches lower or higher prices at the auction markets, thereby affecting both the profitability and productivity of the tea industry. To increase productivity, managers in the tea industry need to pay proper attention to machine utilization, age, modernization, cost, and investment. Results of this study demonstrate that tea managers are aware of and have practical knowledge of sustainability principles, and that these principles are relevant to their businesses. Pressure from customers, particularly, foreign markets drive efforts for adoption of sustainability practices followed by globalization and international pressures. The study also found that adopting sustainable practices have resulted in cost savings in tea production; leads to improvement in product, process quality as well as improvement in efficiency and productivity.

The study further identified and selected most appropriate indicators for sustainability assessment of the tea industry. Using the analytic hierarchy process (AHP), weights for sub-criteria, criteria and sustainable production dimensions in a hierarchically designed sustainable production were obtained. These elements, including respective indicators can be found from the US National Institute of Standards and Technology (NIST). These indicators are the most prioritized indicators that may serve as a guide in the implementation and evaluation of sustainable production initiatives and strategies in the tea industry.

The chapter has also presented a framework to obtain sustainability performance sub-indices in economic, social, and environmental categories, and provides a composite sustainability index for the industry. The result suggests that the Malawian tea industry is at a medium level of sustainability, with an index value of 0.4995 and requires more improvement especially in the environmental and social dimensions of sustainability.

The next chapter presents a novel decision support tool for optimally operating production processes while minimizing cost impacts and maximizing the long term sustainability.

Chapter-7
Model Development

7.1 Introduction

The tea industry faces increasing pressure to reduce costs and incorporate environmental and social issues, while simultaneously ensuring its economic and financial viability. Therefore, decision support tools are urgently needed to provide managers with sufficient options necessary to optimize the balance among all three elements of sustainable performance. However, there is an absence of a specific industry computer-based support system to assist management in the decision-making processes. This chapter presents a novel decision support tool for optimally operating production processes while minimizing cost impacts and maximizing the long-term sustainability. The tool is based on a combination of life cycle analysis (LCA), multi-criteria decision analysis (MCDA), particularly, the analytic hierarchy process (AHP), and multi-objective optimization methods. This chapter consists of five sections including this introduction. The second section describes the structure of the developed tool, and its main features. The subsequent sections contain a brief discussion of the economic, social, and environmental objects considered in this study. The fourth section describes the model solution. The chapter closes with summary findings from this study.

7.2 Decision support model architecture

This section describes the structure and main features of the developed model. A multi-objective optimization and integrated sustainability assessment tool (MOISAT) is proposed to assist with the implementation of sustainable productivity in the tea industry. The developed model aims to assist decision makers in industry in finding the optimal levels of tea production processes while minimizing cost impacts and maximizing the long-term sustainability.

7.2.1 MOISAT

MOISAT is a spreadsheet program written for use in the commercial software, Microsoft Excel®, enabling the user to organize, calculate and analyse data gathered from the tea industry. It makes use of macros written in the Visual Basic for Applications (VBA) programming language. In this tool, Microsoft Excel® is used as data manager, which acts as working platform linked with database module (Microsoft Access®) and MATLAB for multi-objective optimization. MOISAT is divided into three modules according to its capabilities: database management; user interface; and model base management. The database management system collects, organizes and gives the user access to the data. The model-based system handles the use of models that is part of the system. The developed tool comprises eight sub-models: (1) the economic – which enables the user to provide equipment design specifications and economic parameters for performing investment analysis; (2) environmental model; (3) social model; (4) process model; (5) analytic hierarchy process model; (6) technology options model; (7) optimization model; and (8) report writer model. The user interface module is the gateway to the database management system, and model-based management system. These modules are used to construct the basic structure of the proposed system in order to fulfil the objectives of this work. The system architecture of MOISAT is presented in Figure 7-1. The details of these modules are presented in the following sections.

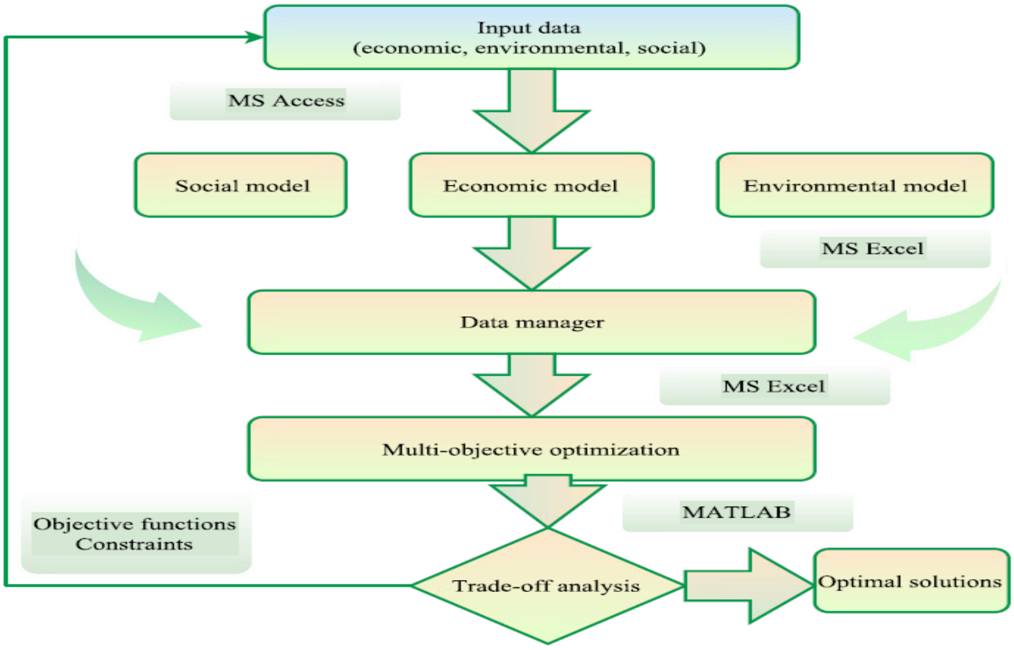

Figure 7.1: MOISAT modelling framework

7.2.2 Database management system (DBMS) module

Database management system (DBMS) module performs the function of storing and maintaining information used by the decision support system. Haastrup *et al.* (1998) observe that “a database management system is responsible for the retrieval, updating and visualization of the information required, and is composed of a database and a management system”. Stated differently, the database is designed and implemented in order to present all the relevant data, while the DBMS comprises the software required to create, access and update the database. The data management module, therefore, consists of both the DSS information and the DSS database management system. The DBMS has been developed in Microsoft Access® and contains twenty-four forms that are organized in four main categories: factory, farm, revenues, and social. Users are required to capture data such as, amount of green leaf processed, made tea production, energy consumption, factory and field operation man days (human labour), machinery (tractor usage), daily tea sales, as well as five social issues related stakeholder categories (workers, consumers, local community, society, and value chain actors). Figure7.2 illustrates a screenshot of user interface for data entry.

Figure 7.2: User interface for data entry

7.2.3 Model-based management system (MBMS)

The model-based management system provides decision-makers with access to a variety of models, which are developed for the specific application to aid decision-makers in the decision-making process. MBMS provides formulation, analysis and interpretation capabilities between the user interface and the model. It also provides ways of interpreting the results from the analysis of alternatives. The model-based management system stores and maintains the DSS's models, and its function of managing models is similar to that of a database management system. The model-based management system adopted in MOISAT is composed of six main components: economic, social, environmental, process, decision support, and optimization model. These models allow the tool not only to provide information to the user, but assist the user in making a decision. To that end, five out of six models are constructed using spreadsheets. Spreadsheet modelling has been chosen for the following reasons: firstly, spreadsheets can easily store relatively large amounts of data in rows and columns on multiple worksheets. Secondly, they can perform calculations using spreadsheet functions or a programming language. Thirdly, spreadsheet software offers a variety of graphical user interface (GUI) options from basic formatting and drawing tools to more advanced GUI features such as user forms and control tools. Thus, a user is able to access and analyse data, perform problem solving, and interact with a GUI through a spreadsheet decision support system. The details of the models forming the MBMS model are presented in the following sections.

(1) Economic model

The main purpose of the economic (ECON) model is to provide economic parameters for economic assessment of tea operations. The ECON model acts like inventory tables, which collect or deposit parameters for performing economic analysis of tea operations. It is developed in Microsoft Excel® and contains seven worksheets: model inputs, calculations, sensitivity analysis, summary results, economic indicators, scenarios, and charts. The model inputs worksheet enables the user to provide economic specifications. The economic parameters include information such as costs (raw materials, product cost, transport); utilities price (electricity, diesel, firewood, steam); general product information (operating labour, operating supplies, overheads, taxes, insurance, etc.); cash flow information (working capital, discount rates); and equipment and operating cost.

ECON model assumes (i) the cost of raw materials, equipment, utilities, selling price of made tea are estimated on international prices and standard reference texts; (ii) all the purchases of the equipment employed for specific tea factory machines such as withering troughs, continuous oxidation units (COU), cut-tear-curl (CTC) and rotor vanes, fluidized bed dryers, and sorting machines are specified by the user. Key economic evaluation results are calculated using standard formulas and results are shown in the summary results worksheet. Economic indicators considered for the economic performance of the tea industry are the net present value (NPV), internal rate of return (IRR), and total annualized costs (TAC). The scenarios worksheet assists the user to explore three scenarios: base case, worst case and most likely scenarios. The sensitivity analysis sheet enables users to carry out sensitivity tests. The main objective of performing sensitivity analysis is to determine the critical variables of the economic model. Such variables are those whose variations have the greatest impact on the economic results. Examples of sensitivity factors applied in this study are sales price, capital expenditure, operating expenses.

(2) Environmental model

The primary function of the environmental (ENV) model is to facilitate automated calculation of parameters used for environmental assessment of the tea industry's operations. The model incorporates the key aspects of life cycle assessment (LCA) methodology, which is used to evaluate the environmental impacts of tea production. LCA is a systematic, cradle-to-grave process that has largely been applied to quantify the environmental impacts of products, processes, and services. The structure of the ENV model follows the ISO standards 14040:2006 and ISO 14044:2006 framework that comprises four main steps: (i) goal and scope definition; (ii) life cycle inventory; (iii) life cycle impact assessment (LCIA); and (iv) implementation. The ENV model contains eight worksheets. The inventory sheet performs an inventory of mass and energy flows retrieved from the database. Characterization, normalization and weighting worksheets (LCA step 3) classify and characterize the types of environmental impacts and calculate them with respect to substances emitted from the life cycle of tea and characterization factors for each impact category. Calculated results are summarized in the LCIA results sheets while detailed results are provided in graphic and tabular forms, shown in two separate sheets namely, "detailed results" and "view charts".

(3) Social model

The objective of this model is to evaluate the social performance of the Malawian tea industry. Social performance encompasses the entire set of processes implemented by a company to generate outcomes for its clients and the communities it operates. The social (SOC) model, like the environmental model, uses the four phase structure proposed by the UNEP/SETAC guidelines of (i) goal and scope definition, (ii) inventory analysis, (iii) impact assessment, and (iv) interpretation (Benoît & Mazijn, 2009b). Accordingly, the first step details several critical issues of a social life cycle study, such as study group, intended audience, system boundary, and the functional unit. The SOC model contains eight worksheets. The inventory worksheet is used to collect data retrieved from the database and derive life cycle inventory (LCI) results. The social life cycle impact assessment sheet converts LCI results into indicators of impact categories. To quantitatively evaluate the social impacts of tea production, users are required to go through three stages: (1) select stakeholders and subcategories according to their importance and relevance to the tea industry; (2) determine the weighting factors of each sub-category through a questionnaire survey to local experts, and (3) develop the method by making reference to the established guidelines. In this module, MOISAT covers the cradle-to-gate system boundary, spanning from tea cultivation, growing, harvesting, and processing, but excludes the nursery and usage stages from the system boundary.

(4) Decision support model

The purpose of this model is to support team contributions to decision-making. It is designed to allow input from different stakeholders involved in the decision-making process in the tea supply chain. The DSS model has adopted and follows the concepts of the analytical hierarchy process (AHP), which is an approach designed to assist in the decision-making process for problems associated with multiple criteria (Saaty, 2000). This process begins with structuring of the problem so that it is decomposed into a hierarchy of sub-problems. Then, the decision-maker evaluates the relative importance of these sub-problems (criteria) by pairwise comparison, where the degree of importance is given to each criterion in relation to another. The AHP method converts these evaluations to numeric values (weights and priorities), which are used to calculate a score for each alternative. A consistency rate measures the extent to which the decision-maker has been consistent in comparison.

The proposed DSS model embedded in MOISAT has six worksheets: selection of indicators, pairwise comparison, computations, results, sensitivity analysis, and evaluation. The objective of the model is to select indicators of sustainable performance: environmental, social, and financial. Selection of these indicators is carried out by performing the following procedure: Firstly, the indicators are determined. Thereafter, the criteria are chosen based on the users' preferences, and the weight of each criterium is calculated using pair-wise comparison from the AHP. The indicators in each sustainability dimension are ranked based on the chosen indicators criteria and those with the highest scores are then selected.

To identify the relevant sustainability indicators for the tea industry, stakeholder judgments, values and preferences are crucial. In this model, the decision-maker is required to follow these steps: (1) rank the indicators, technologies, or objectives in order of their importance; (2) assign a score to each alternative, typically between zero and one, representing a range from the worst to best possible alternative; (3) perform a sensitivity analysis. The DSS is also linked to the environmental, social, and economic models. To select the relevant indicators, users need to provide the weights in the corresponding cell for each decision matrix, which automatically calculates the eigenvalue. Furthermore, the module is equipped to calculate the assessment score, normalized score, and final score index for each criterion. Finally, results are summarized in the "Results" worksheet and an evaluation is done.

(5) Optimization model

The purpose of this model is to perform optimization of selected sustainability performance indicators of the tea industry. The optimization model has been coded using MATLAB, and implements a Microsoft Excel® interface with a MATLAB-Excel link that allows the user to introduce the required data and recover the results. Therefore, no MATLAB skills are required to run this part of the decision support system. The core of this model is a set of equations to describe the objective functions and the constraints of the problem. The objective functions modelled in the tool are based on costs, emissions, and social benefits. These represent the major issues confronting the tea industry and therefore, threatening its competitiveness and survival. The problems are conflicting and therefore, multi-objective in nature, which will require simultaneous optimization of three objective functions of: minimizing production costs, minimizing environmental impacts, and maximizing social benefits. Data retrieved from the database management system is provided through an Excel spreadsheet to the optimizer, which then generate solutions. More specifically, the system feeds that data into the model so that it can calculate sustainability performance measures such as net present value (NPV), life cycle environmental impacts, and social benefits like total number of jobs created. The outputs of the system are then displayed and provided as an Excel spreadsheet file. Finally, the system user has to decide whether further changes are necessary to the tea production system.

(6) Report writer model

The main function of the report writer model is to generate monthly and annual reports for operation activities of the tea industry. The need for including operational reports was identified during interviews with lower level managers of the industry. Stakeholders highlighted the need for automating the production of the monthly factory and field operations report. Various reports can be generated by this DSS. These include factory green leaf and made tea production, factory labour, energy consumption, fertilizer and pesticide application, monthly tea sales, and field labour, to cite but a few.

7.2.4 User interface module

The user interface module provides the decision maker with the necessary controls for, and possibly feedback about, managing the data and the models. It allows the user to interact with the database and the other parts of the system. Consequently, the objective of the interface module is to allow the user to create, update and update database files and decision making via DBMS and MBMS. The user interface is arguably one of the major factors that determines the success or failure of software. In this work, a front-end user interface for obtaining data through the tea industry has been designed for MOISAT. Individuals in various departments of the tea enterprise (who fill in the data in the specified format since these users will not necessarily be computer experts, the interface should be simpler and user-friendly) will use the front end. The snapshot of MOISAT user interface is given in Figure 7-3.

Figure 7.3: Graphical User Interface for MOISAT

7.3 Model Formulation

This section covers the mathematical modelling of tea process decision–making problems addressed by this study.

7.3.1 Economic performance indicators

Economic performance is undeniably, one of the primary objectives of any business organization. To ensure that these organizational objectives are being achieved, it is imperative to establish suitable key performance indicators that will inform managers and decision makers in industry at any time, whether the business is going in the direction or not. Moreover, any management decisions should be based on a good knowledge of the current state of the business, which is not possible without a system of performance indicators to inform management about the results in all key activities and processes of the company. Well-known methods for measuring the economic performance of a business organization include return on investment (ROI); payback period (PBP); return on equity (ROE); return on assets (ROA); internal rate of return (IRR); total annualized cost (TAC); and net present value (NPV). Comprehensive discussion of these terms is beyond the scope of this study.

NPV and IRR are arguably the most effective and broadly available financial measures to assess business performance (Pintarič & Kravanja, 2006), and their analysis provide a powerful tool in making informed decisions. Furthermore, entrepreneurs often use NPV and IRR since they provide more appropriate profitability measurement in design evaluation. In addition, both can be used together to provide a comprehensive profitability measurement as well as to enable comparison of alternatives. Based on the reasons above, these indicators will be used to describe the economic performance of the tea industry. Brief discussions of these indicators are given in the following subsections.

1. Net Present Value (NPV)

Net present value (NPV) is the sum of the present values of the future cash flows. NPV can be calculated by the summation of all present values of all incomes minus the summation of the present values of all expenditures. The NPV can be expressed as:

$$NPV = \sum_{y=1}^{Y} \frac{CF_{A,y}}{(1 + r_d)^y} - C_{TCI} \tag{40}$$

where CF_A is the total annual cash flow after the base year for year y; r_d represents the interest rate (discount rate, %); Y is the project investment life time after the base year. C_{TCI} is the total capital investment before the base year and is the summation of the total fixed capital investment, C_{FCI}, and the working capital cost, C_{WCC} (Turton *et al*., 2012). The fixed capital cost represents the cost of modernizing a tea factory. $C_{FCI}$is the summation of the total bare module costs of the equipment (*TPEC*); installation; piping; instrumentation and controls; insulation; electrical equipment and materials; building; yard improvements; contingency fees, auxiliary and service equipment (Gunthrie, 1969; Turton *et al.*, 2012; Ulrich, 1984).

The total capital investment for tea factory machinery includes the withering trough costs, CTC and rotor vane costs, continuous oxidation unit (COU) cost, fluidized bed dryer, and sorting and packing cost. Total bare module capital cost is the sum of the cost of each piece of equipment in the modernization process. Contingency fees are defined as a fraction of the total bare module capital cost to cover unforeseen circumstances as well as contractor fees. Auxiliary and services include items such as installation of electrical and water systems; and typically account for up to 30% of the total bare module capital cost and contingency fees. Working capital cost represents costs incurred in day-to-day operation a plant and is usually divided into three categories: direct manufacturing costs, indirect (or fixed) manufacturing costs, and general expenses. Direct manufacturing costs consists of raw materials, operating labour, supervisory and clerical labour (10-25% operating cost), utilities, maintenance and repairs (2-10% of fixed capital), operating supplies (2-10% of maintenance and repairs), laboratory charges, and expenses for patents and royalties. Indirect manufacturing costs include overheads, packaging, storage (warehousing), local taxes, insurance and depreciation. General expenses include administrative costs, distribution and selling costs, and research and development charges.

Total fixed capital investment (C_{FCI}) cost is given by the sum all purchased equipment (*TPEC*) cost of the components of the tea manufacturing system multiplied by a factor β, as given by

$$C_{FCI} = \sum_{q} TCI_q = \sum_{q} \beta TPEC_q = \beta \sum_{q} TPEC_q = \beta TPEC \tag{41}$$

where $q = 1, 2, \ldots., Q$ denotes the q^{th} component, and Q is the total number of components. The equipment purchase cost of unit q in the year of interest is determined as a function of the purchase cost (PEC_q) of the unit at the reference year (base year). The Chemical Engineering Plant Cost Index (*CEPCI*) is used to account for the effect of inflation of the equipment cost from the reference year as given by Eq. (42).

$$TPEC_q = PEC_q \left(\frac{CEPCI_{2013}}{CEPCI_{base\ year}} \right) \quad \forall q \in Q_{eq} \tag{42}$$

The purchase cost of each unit involved in the tea process plant at the reference year is given by the following expression.

$$CL_{jst} = CL^0_{jto} \frac{I_t}{I_{to}} \left(\frac{CAP_{sjt}}{CAP^0_{sto}} \right)^{0.6}, \forall s, j, t \tag{43}$$

where CL_{jst} is the capital investment, CAP_{jst} required plant capacity using technology j at factory s during time interval t, CL^0_{sto} capital expenditure to install a similar plant of capacity CA^0_{sto}, and I_t is the *CEPCI*. This study proposes to increase the capacity of fluidized bed dryers from 400 kg/h of made tea to between 600 kg/h and 800 kg/h.

The cash flow that appears in Eq. (40) is determined from the net earnings (i.e. profit after taxes), and the fraction of total depreciable capital. The net earnings are given by the difference between the incomes (*RV*) and costs and taxes (total cost (TC_{tot})). The revenues (continuous variable RV) are determined from the sales of made tea and the corresponding prices:

$$RV = \sum_{k \in K} Z^p_{jk} . \gamma^{FP}_{lpt} \qquad k = 1,2, \ldots., K \tag{44}$$

where Z_{jk}^{p} is the annual production of tea in kilograms, k represents the set of tea grades that can be sold, and γ_{lpt}^{FP} is a parameter that denotes the market price of tea grade k in US$/kg made tea. The revenue of the sales for each year depends on the amount of tea produced in that year and its price.

The total cost (TC_{tot}) of tea production accounts for purchase of raw materials (denoted by the continuous variable $COST_{material}$), factory operating costs ($COST_{op}$), the cost of transporting materials between tea farms or forests and factories ($COST_{transport}$), given by Eq. (45).

$$TC_{tot} = COST_{material} + COST_{op} + COST_{transport} \quad (45)$$

Raw material costs are obtained using the amount and price of raw materials consumed as shown in Eq. (46).

$$COST_{material} = \sum_{r \in R} CR_{i}^{r}.Y_{i}^{r} \qquad r = 1,2, \dots, R \quad (46)$$

In this equation, R is a set of raw materials (green leaf, fertilizers), CR_{i}^{r} is a parameter that represents the per unit cost of raw materials.

The annual operating costs$\left(COST_{op}\right)$ of a tea company is the sum of variable operating costs, which is shown in Eq. (47). The variable costs include the costs for operating a tea factory, such as utilities (firewood, electricity, and steam), labour, and maintenance. The maintenance cost account for the general maintenance of tea factory machines, and it is assumed to be 5% of the capital cost.

$$COST_{op} = COST_{wood} + COST_{power} + COST_{steam} + COST_{labour,op} + COST_{maint} \quad (47)$$

The cost of utilities, denoted by the continuous variable $COST_{ut}$, is obtained from the amount of utilities that are purchased externally and their corresponding per unit cost, as given in Eq. (48).

$$COST_{ut} = \sum_{u \in U} TCONS_{u}.COST_{u}^{UT} \quad (48)$$

where $TCONS_{u}$ is the total amount of utility u consumed and parameter $COST_{u}^{UT}$ denotes the per unit cost of utility u. Eqs. (49) and (50) determine the annual power and steam consumption costs, respectively.

$$COST_{power} = T_{op}.P_{kWh}^{el} \sum_{q \in Q} E_{c}^{q} \quad (49)$$

$$COST_{steam} = C_{stm}\,\dot{D}_{stm}.T_{op} \quad (50)$$

where P_{kWh}^{el} is the unit cost of power in US$/kWh, E_c^q represents electricity consumption of machines, $\dot{D}_{stm}$ denotes steam consumption rate (kg/h), C_{stm} represents steam cost per unit (US$/kWh), and T_{op} is the annual operating hours of the tea factory. Firewood cost required for tea processing can be calculated using the following expression:

$$COST_{wood} = C_i^f \, . X_i^f \tag{51}$$

where C_i^f is the unit cost of firewood in US$/m^3 and X_i^f is the annual firewood consumption in tea factory (m^3). Factory labour input for tea processing consists of (a) direct workers, (b) indirect workers, (c) supervisors, and (d) officers and managers. Eqs. (52) and (53) are used to calculate the labour cost.

$$COST_{Labour,op} = \sum_{a=1}^{n} \sum_{d=1}^{m} C_{a,d}^f X_{a,d}^f \tag{52}$$

$$COST_{Labour,op} = \sum_{j=1}^{B} \beta_{kj}^{LC} . \alpha_{kj}^{NC} \tag{53}$$

where a is the index of jobs (a= $1, 2, \dots, n$), d is the number of workers, ($d = 1, 2, \dots, m$), n represents the total number of jobs, m is the total number of workers, C_{ad}^f is cost of job a when d workers are assigned, $X_{a,d}^f$ = 1 if d workers are assigned to job a or otherwise =0. β_{kj}^{LC} represents total wages and benefits per period of category of the *i*th labour, α_{kj}^{NC} = the number of labour in *j*th category, and *B* = number of categories of labour.

Transportation costs from tea fields to the factory can be expressed as

$$COST_{irt}^{FA} = \sum_{i=1}^{I} \sum_{r=1}^{R} \sum_{t=1}^{T} TC_{ti}^r . \lambda_{ij}^{RM} . TY_{ti}^r \tag{54}$$

where TC_{ti}^r is the unit transport cost (\$(tons) $^{-1}$ km^{-1}) of transporting tea from different fields to factories. Equation (55) presents the depreciation term, calculated with the straight-line method in which d is the depreciation and sv is the salvage value. In this equation FCI denotes the total fixed cost investment, which is determined from the capacity expansion made in factories.

$$d = \frac{(1 - sv)FCI}{Y} \qquad \forall \, y \tag{55}$$

Substituting Eqs. (41) to (55), the overall equation for calculating the NPV of an investment is expressed as:

$$NPV = \sum_{y=1}^{Y} \Bigg[\Bigg(\sum_{k \in K} Z_{jk}^{p} . \gamma_{lpt}^{FP} - \Bigg(\sum_{r \in R} CR_{i}^{r} . Y_{i}^{r} + E_{c}^{q} . P_{kWh}^{el} + C_{stm} \dot{D}_{stm} . T_{op} + C_{i}^{f} . X_{i}^{f} + \sum_{j=1}^{B} \beta_{kj}^{LC} . \alpha_{kj}^{NC} + \sum_{i=1}^{I} \sum_{r=1}^{R} \sum_{t=1}^{T} TC_{ti}^{r} . \lambda_{ij}^{RM} . TY_{ti}^{r} + 0.05 C_{TCI} \Bigg) - \left(\frac{(1 - sv) FCI}{Y} \right) \Bigg) . \left(1 - \frac{\emptyset}{100} \right) + \frac{(1 - sv) FCI}{Y} \Bigg] . \frac{1}{\left(1 + \frac{r_d}{100} \right)^{t}} - C_{TCI} \quad (56)$$

where $\emptyset$ denotes the income tax.

2. Internal Rate of Return (IRR)

IRR is the interest or discount rate for which the NPV is equal to zero (Turton *et al.*, 2012). It is a measure of the maximum after interest or discount rate at which the investment can break even (ibid). It is, therefore, at that point that the values of r_d or interest rate of return, r_{ROR}, can be readily determined. More often, business corporations will set an “internal” interest rate, which is the minimum acceptable rate of return that a company will accept for any new investment. However, acceptance of this discount depends on other factors like the prevailing economic situation, environmental regulation, and social needs. A project investment which yields IRR greater than the internal interest rate is considered to be profitable. Peters and Timmerhaus (2003) assert that the combined use of NPV and IRR can reflect a comprehensive assessment that includes the rate of return and its investment scale. Furthermore, IRR can also be compared directly with interest rate, and is sometimes known as interest rate of return or discounted cash flow rate of return (DCFROR). IRR is calculated using the following as follows (Tower & Sinnott, 2012):

$$0 = \sum_{y=1}^{Y} \frac{CF_{A,y}}{(1 + r_d)^{y}} - C_{TCI} \quad (57)$$

3. Total Annualized Cost (TAC)

The total annualized cost (TAC) comprises the annual capital, operating and maintenance costs and it can be calculated as follows (Turton *et al.*, 2012):

$$TAC = C_{FCI}\left[\frac{r_d(1+r_d)^n}{(1+r_d)^n-1}\right] + C_{op} \tag{58}$$

where C_{FCI} is investment cost in the base year (US$/year), r_d represents the discount (interest rate) per year [-], n denotes the lifetime of equipment/plant (years), C_{op} is the operating and maintenance cost per year (US$/year). The annualized factor, also known as capital recovery factor, is calculated by the Eq. (59).

$$CRF = \frac{r_d(1+r_d)^n}{(1+r_d)^n-1} \tag{59}$$

7.3.2 Environmental performance indicators

This section provides details for calculating the environmental performance of the Malawian tea industry. To evaluate the environmental impacts of the tea industry, a combined approach that embeds life cycle assessment (LCA) principles within a multi-objective optimization framework is followed (Azapagic & Clift, 1999b; Stefanis *et al.*, 1995). LCA is a systematic, cradle-to-grave process that has been largely applied to quantify the environmental impacts of products, processes, and services. The structure of the LCA model on which this analysis is based follows the ISO standards 14040:2006 and ISO 14044:2006 framework which comprises four main steps: (1) goal and scope definition; (2) life cycle inventory; (3) life cycle impact assessment (LCIA); and (4) implementation (ISO, 2000). For a detailed discussion of these steps, interested readers are referred to chapter 3 of this thesis.

(1) Goal and scope definition

The goal of this study is to develop an understanding of the environmental impacts of the tea production in Malawi. The scope of the study is to develop a "cradle-to-gate" life cycle assessment of tea operations, which includes tea growing (cultivation), transportation, and processing. The system boundary for the studied enterprises starts at the farm where tea is grown and ends at the production of dried tea at the factory gate. Upstream activities[3] and downstream activities[4] (e.g. distribution and use stage) have not been included in the system.

(2) Life cycle inventory

The life cycle inventory (LCI) involves the collection of environmental impact data necessary to meet the goals of this study. The objective in this phase is to perform mass and energy balances to quantify all the materials, energy inputs, and wastes as well as emissions from the system that cause the environmental burdens. Inputs are raw materials such as agrochemicals, energy, water, etc. Outputs are made tea and by-products, emissions to air, water and soil, and wastes. Following Azapagic and Clift (1999b), environmental burdens are then quantified according to Eq.(60):

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[3] Tea refers to cultivation at nursery stage. This further extends to activities covering the production and transportation of farm inputs such as diesel, fertilizers, pesticides

[4] Distribution and usage stage, mostly shipment of made tea to the regional and overseas markets

$$EMS_j = \sum_{i=1}^{I} bc_{j,i}\, x_i \qquad j = 1, 2, \ldots, J \tag{60}$$

where EMS_j is the total burden from the production system, $bc_{j,i}$ is burden j from process or subsystem i and x_i is the mass or energy flow associated with the subsystem. In this study, the environmental burdens of particular interest include: carbon dioxide (CO_2), methane (CH_4), nitrogen oxides (NO_x), ammonia (NH_3), carbon monoxide (CO), hydrocarbons (HC), particulate matter (PM_{10}), heavy metals, sulphur oxides (SO_x as SO_2), and nitrous oxide (N_2O). The following sections provide details on these burdens can be determined.

Equation (61) can be used to calculate the total environmental burdens (EMS_{tea}^{TOT}) associated with tea production system.

$$EMS_{tea}^{TOT} = EMS_{tea}^{Cultivation} + EMS_{tea}^{Transportation} + EMS_{tea}^{Processing} \tag{61}$$

where

$$EMS_{tea}^{Cultivation} = EMS_i^{FERT} + EMS_i^{LIME} + EMS_{Mi}^{PEST} + EMS_{Mi}^{FF} \tag{62}$$

$$EMS_i^{FERT} = \sum_{f=1}^{F} (EMS_{nutrient}^{N} + EMS_{nutrient}^{P} + EMS_{nutrient}^{K}) \tag{63}$$

Emissions of greenhouse gases (GHG) as well as non- GHG from nitrogen, phosphorus and potassium (NPK) fertilizer application in tea farms are quantified according to Eqs.(64), Eq.(65) and Eq.(66), respectively (IPCC, 2006).

$$EMS_{nutrient}^{N} = \sum_{g} (A_{i,g}.AR_{nitrogen,g}.EF_{nitrogen,g}) \tag{64}$$

where A_i is area applied (ha); $AR_{nitrogen}$, $AR_{phosphorus}$, and $AR_{potassium}$ are nitrogen, phosphorus, and potassium application rates (kg/ha), respectively. $EF_{nitrogen}$, $EF_{phosphorus}$, and $EF_{potassium}$ are emission factor nitrogen, phosphorus, and potassium fertilizers, respectively.

$$EMS_{nutrient}^{P} = \sum_{g} (A_{i,g}.AR_{phosphorus,g}.EF_{phosphorus,g}) \tag{65}$$

$$EMS_{nutrient}^{K} = \sum_{g} (A_{i,g}.AR_{potassium,g}.EF_{potassium,g}) \tag{66}$$

Emissions of gases from the application of agricultural lime in tea farms are quantified according to Eq.(67) (IPCC, 2006).

$$EMS_g^{LIME} = \sum_g (A_i . AR_{Lime,g} . EF_{Lime,g}) \tag{67}$$

Emissions from pesticide application are calculated by multiplying the quantity of average application rate of active ingredient $(A.I_i)$ in kg per hectare per year and the emission factor EF_i. However, it has to be noted that at the time of writing, most tea companies in Malawi had stopped applying pesticides. Therefore, emissions from pesticides are excluded in this model.

$$EMS_i^{PEST} = E_i^{Herbicides} + E_i^{Insecticides} + E_i^{Fungicides} \tag{68}$$

$$EMS_i^{Herbicides} = \sum_g (A_i . A.I_{g,herb} . EF_{g,herb}) \tag{69}$$

$$EMS_i^{Insecticides} = \sum_g (A_i . A.I_{g,insect} . EF_{g,insect}) \tag{70}$$

$$EMS_i^{Fungicides} = \sum_g (A_i . A.I_{g,fungi} . EF_{g,fungi}) \tag{71}$$

Emissions due to diesel combustion used for agricultural operations are calculated by multiplying the emission factor of the fuel by the amount needed per hectare, as given in Eq. (72).

$$EMS_{op}^f = \sum_{op} (\beta_{f,op}^p . FC_{f,op}^u . CEF_{f,op}^k) \qquad \forall op \in O \tag{72}$$

where EMS_{op}^f direct emissions for producing one hectare of green tea, $\beta_{f,op}^p$ direct quantity of fossil fuel (diesel) for producing one hectare of green tea; $FC_{f,op}^u$ average energy content of fuel; and $CEF_{f,op}^k$ emissions of fossil fuel per unit of energy.

Emission of both greenhouse and non-greenhouse gas caused by transportation depend on the transport mode used and the volume of transported materials. Eq. (73) can be used to determine total transportation emissions.

$$EMS_{tea}^{Transportation} = \sum_{p=1}^{P} \sum_{r=1}^{R} \sum_{t=1}^{T} \sum_{i=1}^{I} A_t^{pr} . TY_{ti}^r . X_{ij}^{RM} \tag{73}$$

Eq. (74) can be used to determine emissions resulting from diesel and firewood combustion at the tea factory:

$$EMS_{tea}^{Processing} = \sum_{m=1}^{M}\sum_{p=1}^{P} A_m^p . Z_{jk}^p . X_{ijm}^{PL} \tag{74}$$

(3) Life cycle impact assessment (LCIA)

The purpose of this life cycle phase is to translate the burdens quantified in the LCI into related potential environmental impacts (or category indicators). The impact assessment in LCA consists of the following mandatory elements of: selection (of impact categories, category indicators, and LCIA models); classification; and characterization as well as optional elements of normalization and valuation (ISO, 2006a, 2006b). Classification involves assigning the emissions and resources identified by the LCA to specific impact categories. Characterization is the conversion of LCI results to common values within each impact category, so that results can be aggregated into category indicator results. The ISO 14040 also suggests optional elements that can be included in an LCA: normalization, weighting and grouping. Normalization expresses potential impacts in ways that can be compared. Valuation is the assesses that the relative importance of environmental burdens identified in the classification, characterization, and normalization stages by assigning them weighting which allows them to be compared or aggregated. Grouping assigns impact categories into one or more groups and sorts them based on geographical relevance and company priorities, and so on. The last phase of an LCA is to draw conclusions that can support a decision or can provide a readily understandable result of an LCA. These are briefly described in the following sub-sections.

Selection of impact categories: To evaluate the environmental performance of the tea production system some measures [indicators] of performance are essential. The environmental indicators considered in this study are those typically used in LCA and include, but not limited to, global warming potential (GWP), acidification potential (AP), ozone depletion potential (ODP), photo oxidant formation (POCP), eutrophication potential (EP), aquatic toxicity potential (ATP), human toxicity potential (HTP), and terrestrial toxicity potential (TTP). These impacts are calculated using the methodology presented by (Guinee *et al.*, 2001). The details of each impact category and calculation formulas are described in the following subsections.

Global warming potential (GWP) indicator measures the contribution to the global warming caused by the emission of greenhouse gases in the atmosphere. GWP can be calculated using the following expression:

$$GWP = \sum_{p=1}^{P} GWP_p . EMS_p \qquad p = 1, 2, \ldots, P \tag{75}$$

where EB_p represents the emission of greenhouse gas p, GWP_p denotes the global warming factors for greenhouse gas j, expressed relative to the global warming potential of carbon dioxide (CO_2). The GWP depends on the time spent in the atmosphere by the gas, and on the gas's capacity to affect radiation. In this study, we have considered a time span of 100 years adapted from IPCC Fifth Assessment Report, 2014 (AR5). Three gases have been considered: carbon dioxide (CO_2) methane (CH_4) and nitrous oxide(N_2O). The GWP values for 100 year time horizon are 1, 28, and 265 for CO_2, CH_4, and N_2O, respectively.

Acidification potential (AP) is based on the contribution of SO_2, NO_x, *HCl*, NH_3, and *HF* to the potential acid deposition. AP is calculated according to the formula:

$$AP = \sum_{p=1}^{P} AP_p \, . EMS_p \qquad p = 1,2, \ldots, P \tag{76}$$

where AP_p represents the acidification potential of gas p expressed relative to the AP of sulphur dioxide (SO_2), and EMS_p is its emission in kg per functional unit.

Ozone depletion potential (ODP) indicates the potential of emissions of chlorofluorohydrocarbons (CFCs) and other halogenated HCs for depleting the ozone layer and is expressed as:

$$ODP = \sum_{p=1}^{P} ODP_p . EMS_p \qquad p = 1,2, \ldots, P \tag{77}$$

where EMS_p is the emission of an ozone depleting gas p and ODP_j denotes the ozone depletion potential of gas p expressed relative to the ozone depletion potential of *CFC-11*.

Eutrophication potential (EP) indicates the enrichment of an aquatic ecosystem with nutrients (nitrates, phosphates) that accelerate biological productivity (growth of algae and weeds) and undesirable accumulation of algal biomass. EP can be calculated according to the formula:

$$EP = \sum_{p=1}^{P} EP_p \, . EMS_p \qquad p = 1,2, \ldots, P \tag{78}$$

where EMS_p is the emission of species such as N, NO_x, NH_4^+, PO_4^{3-}, P and COD and EP_p represents the eutrophication potential of species p expressed relative to PO_4^{3-}.

Photochemical oxidants creation potential (POCP) indicator calculates the potential of tropospheric ozone (summer smog or photochemical oxidation) caused by the release of those gases (*NMVOCs* and NO_x) which will become oxidants in the low atmosphere under the action of the solar radiation. *POCP* can be calculated according to the formula:

$$POCP = \sum_{p=1}^{P} POCP_p \, . EMS_p \qquad\qquad p = 1,2, \ldots, P \tag{79}$$

where EMS_p is the emission of species participating in the formation of summer smog and $POCP_p$ is the characterization factor for photochemical formation of species p expressed relative to ethylene (C_2H_4).

Abiotic depletion potential (ADP) indicates the potential of depletion of fossil fuels, metals and minerals. ADP can be calculated according to the formula:

$$ADP = \sum_{p=1}^{P} ADP_p \, . EMS_p \qquad\qquad p = 1,2, \ldots, P \tag{80}$$

where EMS_p is the quantity of a resource used per functional unit and ADP_p is the characterization factor for abiotic depletion potential of resource p expressed relative to lead antimony S_b.

Human toxicity potential (HTP) can be calculated by taking into account releases toxic to human to three different media, i.e. air, water and soil:

$$HTP = \sum_{p=1}^{P} HTP_{p\,A} \, . EMS_{pA} + \sum_{p=1}^{P} HTP_{p\,W} \, . EMS_{pW} + \sum_{p=1}^{P} HTP_{p\,S} \, . EMS_{pS} \tag{81}$$

where $HTP_{p\,A}$, $HTP_{p\,W}$ and $HTP_{p\,S}$ are human toxicological characterization factors for substances emitted into air, water and soil, respectively, and EB_{pA}, EB_{pW} and EB_{pS} represent the respective emissions of different toxic substances into the air, water, and soil. These toxicological factors are calculated relative to 1.4 dichlorobenzene (1.4-DB).

Ecotoxicity potential (ETP) is calculated using the following expression:

$$ETP_n = \sum_{p}^{P} \sum_{i=1}^{I} ETP_{i,p} . EMS_{i,p} \tag{82}$$

where n (in the range 1-5) represents freshwater aquatic toxicity, marine aquatic toxicity, freshwater sediment toxicity, marine sediment toxicity and terrestrial ecotoxicity, respectively. $ETP_{i,p}$ represents the characterization factor for toxic substance p in the compartment i (air, water, soil), and $EMS_{i,p}$ is the emission of substance p to compartment i.

Characterization: The purpose of characterization in LCIA is to estimate the potential contribution of different interventions (emissions, resource extractions, and land use) to different categories and to sum the amounts of interventions into a single number within each impact category. Calculation of impacts involve multiplying each environmental intervention by the corresponding characterization factor, and summing the results within each impact category. Eq. (83) is used to calculate an indicator result of impact category.

$$EnvCat_k = \sum_{p=1}^{P} CF_{k,p}.EMS_p \tag{83}$$

where $CF_{k,p}$ represents the characterization k for burden EMS_p showing its relative contribution to impact $EnvCat_k$.

Normalization: Normalization involves the calculation of relative contribution to impact to a reference boundary, typically a region or country. The purpose of normalization is to provide understanding of the relevant proportion or magnitude for each impact category of a product system under investigation (ISO, 2000). The impacts can be normalized with respect to the total emissions or extraction in a certain area and over a certain period. This can help assess the extent to which an activity contributes to the regional or global emission impact. However, normalization results should be treated with caution because of the lack of reliable data for many impacts at the regional and global level.

Weighting: The final stage of LCIA is weighing of impacts. It involves assigning relative values or weights of importance to different impacts, allowing integration across all categories. The weights in the weighting step are typically determined by a panel of experts or stakeholders. The overall equation for life cycle impact assessment stages (classification and characterization; normalization; and weighting) is shown in the following equation:

$$EnvCat_k = \sum_{k} \left(\frac{\sum_p \left(E_p \, . R_p\right) . CF_{k,p}}{NF_k} WF_k \right) \tag{84}$$

In this equation, $EnvCat_i$ (impact category indicator) is the indicator value per function unit of impact category k , $E_p \; x \; R_p$ denotes the release of emission p or consumption of resource p contributing to impact category k, $CF_{i,j}$ is characterization factor for combination of p or resource p involved for impact category k, and NF_i and WF_i are normalization and weighting factors for impact category k.

7.3.3 Social Objective Function

Tea companies in Malawi are becoming increasingly aware that the integration of the social aspects of their operations is critical for their survival and success. In addition, various stakeholders in the tea supply chain are demanding improved

social performance. As a result, a number of tea companies have developed CSR policies and management systems to reduce the potential risks and improve their sustainability performance. However, systematic methods to measure social performance are not available. Consequently, there is a need to establish the criteria most greatly affecting tea companies and to choose the most appropriate quantitative and qualitative indicators to measure social performance. Several criteria are available to measure the social performance of a firm: child labour, forced labour, fair salary, working hours, education and training, occupational health and safety, and local employment, among others. Total number of jobs generated (created) and occupational health and safety are probably the most effective and broadly available measures to assess business performance, and these have been adopted in this study.
A brief description of selected indicators applied in this study is provided in the following subsections.

(1) Employment creation

The tea industry is a very labour-intensive industry in Malawi, with plucking accounting for approximately 70% of the work days on estates and 40% of the cost of production (Wal, 2008). To evaluate the social performance of the tea industry, this study proposes to use the number of jobs created per year. The social objective is to maximize the number of jobs created by tea industry, as given by Eq. (85).

$$NJOBS^{Overall} = NJOBS^{agric}_{perm} + NJOBS^{agric}_{seas} + NJOBS^{proc}_{perm} + NJOBS^{proc}_{seas} \qquad (85)$$

Labour input in the tea industry consists of (a) permanent agricultural jobs($NJOBS^{agric}_{perm}$), (b) seasonal agricultural jobs ($NJOBS^{agric}_{seas}$), (c) permanent processing jobs ($NJOBS^{proc}_{perm}$), and (d) seasonal processing jobs ($NJOBS^{proc}_{seas}$). Eq. (86) represents the number of permanent agricultural jobs on a tea field:

$$NJOBS^{agric}_{perm} = T^{perm}_{kj} \, . \, d^{p}_{ji} \, . \, Y^{k}_{xj} \qquad (86)$$

where $NJOBS^{agric}_{perm}$ is the number of permanent agricultural jobs created, T^{perm}_{kj} is the number of working hours per day; d^{p}_{ji} is the number of permanent agricultural workers required per ha of tea grown j, and Y^{k}_{xj} represents the length of the farming season per crop year (days/year). Defining the number of temporary agricultural jobs created as N^{temp}_{kj} (man-hours/ha) and labour requirements for processing stage as β^{p}_{t}, the overall job creation is calculated using the following equation:

$$N^{Overall}_{jobs} = \sum_{i}\sum_{j}\psi^{f}_{k}\left[T^{perm}_{kj}.d^{p}_{ji}.Y^{k}_{xj} + N^{temp}_{kj} + \beta^{u}_{f}\sum_{k}\alpha^{f}_{jk}.\beta^{p}_{t}\right] \qquad (87)$$

where $N^{Overall}_{jobs}$ denotes the overall number of jobs created by tea company, ψ^{f}_{k} fraction of land occupied by tea variety j, β^{u}_{f} is yield of made tea produced from tea variety j, and α_{jk}^{f} is a dimensionless matrix that matches tea types to correct processing technologies.

(2) Occupational health and safety

Occupational health and safety are the key concerns for any business enterprise, and the tea industry is no exception. However, these issues have received less attention by tea executives as they are perceived to be a liability to business. The use of quantified risk assessment problems of managing occupational health and safety has begun to draw attention of managers and decision-makers within the tea industry. Empirical evidence is growing, suggesting that every year numerous accidents take place in the tea industry causing physical injury, disability, property loss and loss of production time. Consequently, there is a need for a tool to evaluate occupational health and safety in the Malawian tea industry. To estimate the injury or illness incident rate, the following formula used by the American Bureau of Labour Statistics has been adopted (BLS, 2011):

$$P_i^D = \frac{\beta_{ik}^D \,.\, 200{,}000}{p_{ik}^B} \tag{88}$$

where P_i^D is the incident rate, β_{ik}^D represents the number of injuries and illnesses, and p_{ik}^B represents employee hours worked. The constant 200,000 represents the equivalent of 100 full time-employees working 40 hours per week, 50 weeks per year, and provides the standard base for incident rates (BLS, 2011). The formula also includes all non-fatal work-related injuries and illnesses that are recordable. To guide managers and decision-makers in the tea industry, Eq. (88) can be modified by applying an exponential function that represents the severity of the injuries or illnesses (ibid). Equation (89) can be used to minimize the incidence rate of the tea industry.

$$P_i^D = \sum_{m=1}^{M} PM_m \sum_{h=1}^{H} e^{\boldsymbol{h}-(\sum \boldsymbol{h})/H} \, I_m^h \, \frac{200{,}000}{p_{ik,m}^B Z_{jk}^p} \tag{89}$$

where $p_{ik,m}^B$ represents hours of work per unit production of tea using processing method m, Z_{jk}^p denotes the quantity of made tea produced, and I_m^h is the number of injuries in severity class h, if processing method m is selected.

Table 7.1: Exponential severity function

h	$h-\left(\sum h\right)/H$	$e^{h-(\sum h)/H}$
1	-3	0.0498
2	-2	0.1253
3	-1	0.3679
4	0	1
5	1	2.7183
6	2	7.3891
7	3	20.0855

Source: Adapted from Chen and Andresen (2014)

Table 7.2: Classification of work-related injuries/illnesses severity

h	Severity class
1	Minor (absent from work for less than 7 days)
2	Moderate (absent from work for less than 30 days)
3	Serious (absent from work for less than 90 days)
4	Severe (absent from work for less than 180 days)
5	Critical (absent from work for less than 365 days)
6	Terrible (occupational disability, not able to work in the job again)
7	Maximal (fatality)

7.3.4 Constraints

The optimization problem is subject to the following constraints:

a) Mass balance constraints

The mass balance must be satisfied for each node in the network. Total amount of green tea variety v acquired from a tea field i at period t ($Y^r_{v,i,t}$) should not exceed its available amount ($GA^r_{v,i,t}$),

$$Y^r_{v,i,t} \leq GA^r_{v,i,t} \qquad \forall v \in V, i \in I, t \in T \qquad (90)$$

where $GA^r_{u,i,t}$ is the available amount of green tea variety v from estate or tea field i at time period t, $v = \{\text{poly clonal, superior cultivars, indian, chinese, and local}\}$.

The mass balance of estate or tea field i at time period t for tea variety v is given by the following equation:

$$Y^r_{v,i,t} = \sum_k \sum_m Xik_{v,i,k,m,t} \qquad \forall v \in V, i \in I, t \in T \qquad (91)$$

where $Xik_{v,i,k,m,t}$ is the amount of green tea variety v shipped from estate or tea field i to factory j with transport mode m in time period t.

For each factory j and raw material, the purchases from all outgrower together must meet the needs of production.

$$\sum_{i=1}^{I} Y_i^r = \sum_{m=1}^{M} X_{ijm}^{PL} U_m^r Z_{jk}^p, \qquad \forall r, \tag{92}$$

where Y_i^r is the purchase of raw material r made by factory j (kg). U_m^r is the amount of raw material r consumed in technology i at factory j (kg). Eq. (93) represents the material balance for each technology i installed at factory j:

$$U_m^r = \mu_{ic} W_{ij} \quad \forall i, j, c \tag{93}$$

where W_{ij} is the flow of product obtained with technology i at factory s (kg), μ_{ic} denotes the material balance coefficient for technology i and raw material r. For each raw material, the purchases are constrained by an upper limit ($\overline{Y_i^r}$), which is given by its availability in the current market place (in kg)

$$Y_i^r \leq \quad \overline{Y_i^r} \qquad \forall j, c \tag{94}$$

Annual amount of green leaf produced is equal the amount processed, both individually for each estate and as a sum, defined by the following constraints.

$$Y_i^r = \sum_{t=1}^{T} TY_{ti}^r, \qquad \forall r, i, \tag{95}$$

$$\sum_{t=1}^{T} \sum_{i=1}^{I} T\, Y_{ti}^r = \sum_{i=1}^{I} Y_{i,}^r \tag{96}$$

b) Capacity constraints

Capacity of the chosen production method must fulfil customer demands, as given by Eq. (97).

$$\sum_{m=1}^{M} X_{ijm}^{PL} CAP_m \geq Z_{jk}^p \tag{97}$$

Equations (98) to (100) describe the total amount of product transported between factory s and all the warehouses must be equal to the total amount of product obtained for the technologies installed at factory s:

$$CAP_{ti}^{r,trans} \geq TY_{ti}^{r}, \quad \forall r, i, t, \tag{98}$$

$$CAP_{i}^{r,supp} \geq Y_{ti}^{r}, \quad \forall r, i, \tag{99}$$

$$\sum_{i=1}^{I} CAP_{i}^{r,supp} \geq \sum_{i=1}^{I} Y_{i}^{r}, \quad \forall r, \tag{100}$$

The binary variables and non-negativity constraints are described using Eqn. (101), to (103).

$$X_{ijm}^{PL} = \{0,1\}, \forall m, \tag{101}$$

$$Y_{ti}^{r} \geq 0 \quad \forall i, r, \tag{102}$$

$$TY_{ti}^{r} \geq 0 \quad \forall r, i, t, \tag{103}$$

7.4 Model solution

The proposed mathematical model seeks to optimize the economic, environmental, and social performance of a tea production system simultaneously. Three indicators are used to measure the economic performance of the Malawian tea industry: net present value (NPV), total cost (TC), and discounted cash flow rate of return (DCFROR). The environmental performance is measured by the environmental impact embedded in per functional unit of tea, evaluated through Life Cycle Assessment (LCA) procedure. Environmental indicators are those typically used in LCA and include, but not limited to, GWP, ODP, AP, EP, HTP, ADP, ETP, and POCP. The social performance is assessed via two indicators: number of jobs created, and occupational health and safety. The multiple objective functions are denoted as f_1, minimize total cost; f_2, minimization of environmental impacts; f_3, maximization of number of jobs created; f_4, net present value maximization; f_5 minimization of total annualized cost; f_6, minimization incident rate of accidents at work places. The multi-objective optimization of the tea industry can be formulated as in the following steps.

$$\min F_1 = \sum_{r=1}^{R}\sum_{i=1}^{I} C_i^r \, Y_i^r + \sum_{m=1}^{M} \left(T_{jm}^{LC}.Z_{jk}^{p}.\alpha_{jm}^{LC} + DP_m.Z_{jk}^{p} + \varphi_{jm.}^{PL}Z_{jk}^{p}\right)X_{ijm}^{PL} + \sum_{i=1}^{I}\sum_{r=1}^{R}\sum_{t=1}^{T} TC_{ti}^{r}.X_{ij}^{RM}.TY_{ti}^{r} \tag{104}$$

$$\min F_2 = \sum_{p}^{P}\sum_{e}^{E}\sum_{i}^{I} FC_e^f . AY_i^f . EF_e^f + \sum_{p=1}^{P}\sum_{r=1}^{R}\sum_{t=1}^{T}\sum_{i=1}^{I} A_t^{pr}\, TY_{ti}^r X_{ij}^{RM} + \sum_{m=1}^{M}\sum_{p=1}^{P} A_m^p\, Z_{jk}^p\, X_{ijm}^{PL} \tag{105}$$

$$\max F_3 = \sum_{i}\sum_{j} \psi_k^f \left[T_{kj}^{perm} . d_{ji}^p . Y_{xj}^k + N_{kj}^{temp} + \beta_f^u \sum_{k} \alpha_{jk}^f . \beta_t^p \right] \tag{106}$$

$$\max F4 = \sum_{y=1}^{Y}\left[\left(\sum_{k\in K} Z_{jk}^p \gamma_{lpt}^{FP} - \left(\sum_{r\in R} CR_i^r . Y_i^r + E_c^q . P_{kWh}^{el} + C_{stm}\, \dot{D}_{stm} . T_{op} + C_i^f . X_i^f + \sum_{j=1}^{B} \beta_{kj}^{LC} . \alpha_{kj}^{NC} + \sum_{i=1}^{I}\sum_{r=1}^{R}\sum_{t=1}^{T} TC_{ti}^r . \lambda_{ij}^{RM} . TY_{ti}^r + 0.05 C_{TCI}\right) - \left(\frac{(1-sv)FCI}{Y}\right)\right) . \left(1 - \frac{\emptyset}{100}\right) + \frac{(1-sv)FCI}{Y}\right] . \frac{1}{\left(1 + \frac{r_d}{100}\right)^t} - C_{TCI} \tag{107}$$

$$\min F_5 = C_{FCI}\left(\frac{\frac{r_d}{100}\left(1 + \frac{r_d}{100}\right)^t}{(1 + \frac{r_d}{100})^t - 1}\right) + \left(\sum_{r\in R} CR_i^r . Y_i^r + E_c^q . P_{kWh}^{el} + C_{stm}\, \dot{D}_{stm} . T_{op} + C_i^f . X_i^f + \sum_{j=1}^{B} \beta_{kj}^{LC} . \alpha_{kj}^{NC} + \sum_{i=1}^{I}\sum_{r=1}^{R}\sum_{t=1}^{T} TC_{ti}^r . \lambda_{ij}^{RM} . TY_{ti}^r + 0.05 C_{TCI}\right) \tag{108}$$

$$\min F_6 = \sum_{m=1}^{M} PM_m \sum_{h=1}^{H} e^{\boldsymbol{h}-(\sum \boldsymbol{h})/H} I_m^h \frac{200{,}000}{p_{ik,m}^B Z_{jk}^p} \tag{109}$$

Subject to the following constraints

$$Y_{v,i,t}^r \leq GA_{v,i,t}^r \qquad \forall v \in V, i \in I, t \in T \tag{110}$$

$$Y_{v,i,t}^r = \sum_k \sum_m Xik_{v,i,k,m,t} \qquad \forall v \in V, i \in I, t \in T \tag{111}$$

$$\sum_{i=1}^{I} Y_i^r = \sum_{m=1}^{M} X_{ijm}^{PL} U_m^r Z_{jk}^p, \qquad \forall r, \tag{112}$$

$$U_m^r = \mu_{ic} W_{ij} \quad \forall i, j, c \tag{113}$$

$$Y_i^r \leq \overline{Y_i^r} \qquad \forall j, c \tag{114}$$

$$Y_i^r = \sum_{t=1}^{T} TY_{ti}^r, \qquad \forall r, i, \tag{115}$$

$$\sum_{t=1}^{T} \sum_{i=1}^{I} T\, Y_{ti}^r = \sum_{i=1}^{I} Y_{i,}^r \tag{116}$$

$$\sum_{m=1}^{M} X_{ijm}^{PL} CAP_m \geq Z_{jk}^p \tag{117}$$

$$CAP_{ti}^{r,trans} \geq TY_{ti}^r, \quad \forall r, i, t, \tag{118}$$

$$CAP_i^{r,supp} \geq Y_{ti}^r, \quad \forall r, i, \tag{119}$$

$$\sum_{i=1}^{I} CAP_i^{r,supp} \geq \sum_{i=1}^{I} Y_i^r, \quad \forall r, \tag{120}$$

$$X_{ijm}^{PL} = \{0,1\}, \forall m, \tag{121}$$

$$Y_{ti}^r \geq 0 \quad \forall i, r, \tag{122}$$

$$TY_{ti}^r \geq 0 \quad \forall r, i, t, \tag{123}$$

Constraint (110) enforces the assumptions that the total amount of green leaf acquired from tea estates should not exceed available amount. Constraints (112) show that the production capacity of the chosen processing method has to fulfil the factory demands. Constraints (115) and (116) show that the amount of green leaf produced must equal the amount processed, individually for each out grower and as a sum. Constraints (119) and (120) depict the capacity limits of tea out growers and the different modes of transportation. Moreover, the processing variable should only take a value of either 0 or 1, which is denoted by constraint (121). The other two decision variables must be nonnegative, which is shown in constraints (122) and (123).

7.5 Chapter summary

This chapter has described the development of a multi-objective optimization and integrated sustainability assessment tool (MOISAT) that would support decision makers in the tea industry in optimally operating production processes while minimizing cost impacts and maximizing the long-term sustainability. The objectives considered in this study are minimization of total cost and environmental impacts; maximization of number of jobs created and net present value maximization; and minimization of total annualized cost and incident rate of accidents at work places. To achieve the goal of this study, a mixed integer nonlinear programming model for the addressed problem was defined. The proposed model combines life cycle analysis (LCA), multi-criteria decision analysis, and multi-objective optimization methods. The mathematical model, the multi-objective genetic algorithm developed and its automatic combination with multi-criteria methods are the major contributors of this work. Moreover, the tool integrates economic, social and environmental aspects of tea production that follows life cycle analysis procedure in a multi-objective framework.

The chapter has also shown the main features of this tool and distinguished three main parts: a module for database management system, a module for model-based management, and a user interface module. The developed model provides a basis for different stakeholders in the tea industry to easily see the trade-offs between different sustainability aspects, allowing them to make informed decisions. Finally, the tool can facilitate decision-making by helping decision-makers to better understand the decision-maker and the consequences of their decision for sustainable production. The next chapter will discuss the application of the model in a typical tea industry in Malawi.

Chapter-8
Model Verification and Validation

8.1 Introduction

The aim of this chapter is to verify, validate and demonstrate the developed tool to support decision-making processes in the Malawian tea industry. This chapter consists of ten sections including this introduction. The second section reviews the literature on model verification and validation. The subsequent sections describe methods employed to verify and validate the structure of the developed tool, and its main features. The fourth section discusses the selection, data collection techniques and implementation of MOISAT at three case studies. This is followed by a presentation of usability testing results in the fifth section. The sixth section investigates the economic and financial aspects of modernizing a tea production system using data from an existing plant. The section also includes a discussion on model inputs and sensitivity analysis. The seventh section deals with the environmental life cycle assessment results of the three case studies. The social life cycle assessment results of the studied tea companies are presented in the eighth section. The ninth section details base case implementation of multi-objective optimization using MOISAT-NSGAII. The chapter closes with summary findings from this study.

8.2 Model verification and validation

Model verification and validation are undisputedly the most incomprehensible parts of developing a model to support decision making (Sargent, 2013). In addition, these processes are widely perceived as an essential component to establishing credibility. Increasingly, it is recognised that no model can be accepted unless it has passed the tests of verification and validation, since these procedures are vital to ascertain the credibility of the model. Therefore, there is a need for the developed tool to undergo comprehensive verification and validation.

Thacker *et al.* (2004) describe verification “as the process of determining that a model implemented accurately represents the developer’s conceptual description of the model and its solution”. The main purpose of model verification is “to ensure that the model is programmed correctly; the algorithms have been implemented properly; and the model does not contain errors, oversights, or bugs” (Carson (2002). Verification is also focused on ensuring that the specification is complete and that mistakes have not been made in implementing the model. More importantly, model verification helps to confirm that all elements of a new system perform according to the intended functions and meet the allocated requirements. Verification proceeds as more tests are performed, errors are identified, and corrections are made to the underlying model, often resulting in retesting requirements to ensure integrity.

In addition, the validation process checks the accuracy of the model's representation of the real system (Carson, 2002). Sokolowski and Banks (2009) described validation as "the process of determining the degree to which a model is an accurate representation of the real world from the perspectives of the intended users of the model". A similar definition is given by Sargent (2013) "substantiation that a computerized model within its domain of applicability possesses a satisfactory range of accuracy consistent with the intended model". Model validation ensures that the model meets its intended requirements in terms of the methods employed and the results obtained. The purpose of validation is to make the model useful in the sense that the model addresses the right problem, provides accurate information about the system being modelled, and to ensure that the model is actually being used.

8.3 Verification and validation of MOISAT model

In order to ensure that the developed tool addressed the needs of the Malawian tea industry, a systematic process of expert verification has been used at every stage of the tool development process. As the first step, expert opinion of professional staff and stakeholders in the tea industry were called to identify issues affecting the sustainable performance of this industry. The consultative process was followed with a detailed baseline study. The findings of the baseline survey were discussed and verified by the majority of tea stakeholders. The data collected was used for model calibration, and a prototype model was developed. Hence, the current model is verified.

The second phase of the model implementation was also conducted in cooperation with key stakeholders and industry professionals. The developed model was demonstrated using data in order to show how the model runs. This stage was particularly important as it allowed tea managers to assess the significance of the model inaccuracies, and better understand any limitations in using the model. The results obtained from the model were compared with the actual plant data. To validate the prototype model, two potential types of testing were considered in this study: system integrated testing and user acceptance testing. The system integrated testing aimed to verify that all related systems in MOISAT maintain data integrity and can operate in the tea industry. It also ensured that all sub-models were integrated successfully to provide anticipated results after which the tool underwent user acceptance testing.

In order to ensure the usability of the developed tool, the author conducted a usability testing with representatives of the Malawian tea industry. The aim of usability testing was to gauge user's experience with the developed system and, thereby, finding any problems that prevent users from completing their tasks, slow them down, or otherwise degrade their user experience (Hertzum, 2016). The focus of the study was to identify problems, collect quantitative and qualitative data, and determine the participant's satisfaction with the developed tool. Stated differently, the usability engineering process was carried out to ascertain that the developed tool was fit for the tea industry and to provide opportunity for refinement and acceptance of the tool. The test was also used to measure whether the developed tool had satisfied the acceptance criteria of stakeholders in the industry or not. The outcome of the tests will also assist to enhance the ability of the researcher to present a refined, useful and more acceptable decision support system to fit the purpose. This validated the current model. Details about the usability engineering process can be found in Nielsen (1992).

8.4 Case study description

8.4.1 Case study selection

The research design for this study is an explorative, descriptive multiple case study that is analysed through quantitative methods, with a small qualitative component. The multiple case study approach was chosen due to the complex nature of the phenomenon at hand, and the need to take a large number of variables into account (Lewin & Johnston, 1997). In addition, multiple case study design was preferred over the single case design because it provides robust and rigorous grounds for good quality research derived from triangulation of evidence compared with single case design (Eisenhardt, 1989; Yin, 2003). Moreover, a multiple case study approach enables the researcher to explore differences within and between cases. The goal is to replicate findings across cases. Additionally, the evidence abstracted from multiple case research is considered more powerful and more compelling (Herriot & Firestone, 1983).

The case study in this chapter discusses implementation of MOISAT at three tea companies in Malawi. The names of these companies are anonymized to maintain their integrity. These were chosen because of their unique characteristics in terms of size, technology, ownership, certification, and willingness to participate in this research. Case 1 as the subject of this study belongs to Malawi's largest multi-national tea company, which accounts for around 50% of all tea produced in the country. Case 2 has the biggest tea factory in the country as well as in Africa, while Case 3 uses a combination of LTP and CTC tea processing technology. Case 1 and 2 are certified by Rain Forest Alliance and have comprehensive sustainability management programmes in place. Case 3 is a locally-owned Malawian company, and currently not certified. Table 8.1 shows a comparison of the three cases being studied in this research.

Table 8.1: Summary of main characteristics of the selected three cases

Estate	Units	Case 1	Case 2	Case 3
Tea area	ha	495	1878.47	2535
Factory capacity	tons/day	100	240	120
Processing technology		LTP	CTC	Dual
Number of employees		1295	5000	3372

Estate	Units	Case 1	Case 2	Case 3
Crop production	kg	10 497 317	21 013 570	11 723 157
Annual made tea production	kg	2 332 737	5 207 960	2 787 880
Electricity consumption	kWh	1 039 854	3 382 945	1 765 986
Firewood consumption	m^3	6 326	23 595	14 076
Diesel consumption	litres	16 709	50 658	15 160
NPK fertilizer	kg	356 400	1 210 450	2 028 000
Nitrogen applied	kg N/ha	158.4	130.9	198
Phosphorus applied	kg P_2O_5/ha	43.2	35.7	54
Potassium	kg K_2O/ha	86.4	71.4	108
Composite manure	kg N/ha			
Urea fertilizer	kg	-	9186	-
Agricultural Lime	kg	374 600	374 600	800 000
Lime applied	kg/ha	2000	2000	2000
Dolomite	kg	561 900	561 900	1 200 000
Dolomite applied	kg/ha	3000	3000	3000

8.4.2 Data collection methods and sources

The data collected in the case study companies is primarily quantitative in nature. Several data sources have been used to limit the effects of interpreting a single data source only. Yin (2009) recommends six types of data collection strategies: interviews, direct observations, participant observations, documentation, archival records, and physical artefacts. Yin further recommends the use of triangulation in case studies, referring to the collection of data through different methods. Triangulation may also involve different kinds of data on the same problem. The main data collection techniques used in this study were interviews, questionnaires, and observation.

The primary data sources included junior and middle managers from several departments in each company. The data source also included interviewing at least one representative of the executive management team, with a view to obtain partial verification of case data. In addition, as the research probed more deeply, interviews were also conducted with two randomly selected data entry clerks and factory engineers. These persons play an important role since they are responsible for capturing the data into the developed system. The interviews sought to evaluate participant perspectives with regard to the developed tool. In total, 15 interviews were held, with an average of 5 interviews per case study.

In order to validate the usability aspects related to the developed tool, the researcher conducted a user acceptance testing study. The main objective of this phase of the study was to identify usability issues related to the developed tool. The data collection techniques used in this part of the study included observations, questionnaires, and follow-up interviews. Six production managers and factory engineers were recruited to participate in this study. These were randomly drawn from a large pool of users in each studied case. To conduct the user testing, a mixed method using quantitative and qualitative analysis were employed.

Data gathered from the questionnaire was analysed using descriptive statistics. The questionnaire was developed using a 5-point Likert scale (1= Strongly Disagree; 2 = Partly Disagree; 3 = Neither Agree or Disagree; 4 = Partly Agree; and 5 = Strongly Agree). These values represent the subjective satisfaction of the users with regard to the developed tool and its functionalities. In addition, each participant was asked to tick all words that best described their user experience with MOISAT and prioritize five words that they thought were most descriptive of the developed tool.

8.5 Case study results and discussions

This section presents and discusses the results of this case study. The analysis presented in this section can be used to address the economic, environmental, and social implications of tea production practices and to support decision-making processes.

8.5.1 Usability testing- results

Table 8.2 presents the overall results from the questionnaire. The results of user acceptance testing indicate that the tool’s usability and performance were satisfactory. Results suggest that the overall mean score was 3.3 with an overall standard deviation of 1.35. Table 8.2 also demonstrates that 75% of the users strongly agree to use the developed tool; found it easy to use; agree that it allows them to achieve higher productivity; and found it pleasant to work with. More than 50% of the users felt confident using the developed tool, and found it easier to learn, consistent and satisfactory for achieving their needs related to tea production processes.

The study also shows that the developed tool is not unnecessarily complex, cumbersome to use, and inaccurate. The results indicated that overall there was a high level of satisfaction with the developed tool. Users described MOISAT as pleasing, complete, simple, fast to use and safe. The study did not find evidence suggesting that the developed tool is irritating, incomplete, complicated, slow to use, or unsafe. The results of this study show clearly the strengths and weaknesses of the developed tool. The results show that usability tests uncovered less problems. Usability problems were mainly related to navigation and data intensiveness.

Table 8.2: User acceptance testing and usability aspects of MOISAT

	Question	Mean
Q1	Program is useful to the tea industry	4.75
Q2	MOISAT is unnecessarily complex	1.25
Q3	Learning to operate the program was easy	4.75
Q4	Additional support is needed to be able to use MOISAT	2.75
Q5	Various functions in this system were well integrated	4.5
Q6	System has too much inconsistency	2.5
Q7	Most people would learn to use this system very quickly	2.75
Q8	System was very cumbersome to use	1.00
Q9	Using this system made me confident	4.00
Q10	Operating the system requires a lot of thinking	2.75
Q11	Using the program was not complicated	4.00
Q12	Using MOISAT was a very frustrating experience	1.25
Q13	System allowed me to achieve very high productivity	4.75
Q14	System gave me wrong results	2.75
Q15	MOISAT can do all the things I would need	4.25
Q16	Working with this system is pleasant	4.75

8.5.2 Economic assessment

This section presents the economic analysis results of the Malawian tea industry. The economic analysis was undertaken following standard methodology described by Peters *et al.* (2011) and Turton *et al.* (2013). The useful lifetime of the investment project was set to 30 years. The depreciation of the capital investment was calculated using a straight-line depreciation method. The feasibility of the tea factory modernization project was determined by estimating the net present value (NPV) and the discounted cash flow rate of return (DCFROR) as described by (Turton *et al.*, 2013). Detailed discussions are given in the following subsections.

1) Capital cost estimation

Total capital investment (TCI) is estimated from the summation of the fixed capital investment (FCI) and the working capital cost. The fixed capital investment of the plant includes the equipment purchase cost; installation; piping; instrumentation and controls; insulation; electrical equipment and materials; building; yard improvements; contingency fees; auxiliary and service equipment (Gunthrie, 1969; Turton *et al.*, 2009b; Ulrich, 1984). The factors used in determining the FCI are treated in the procedure recommended by Seider *et al.* (2004). Table 8.3 presents the purchased equipment costs for the base case. The cost of the main equipment such as cut-tear-curl (CTC) machines, rotor vanes, fluidized bed dryers, continuous oxidation units (COUs), continuous withering troughs as well as auxiliary equipment (e.g. piping, insulation, electrical equipment, instrumentation) was determined based on correlations found in the literature (Turton *et al.*, 2009a) which relate the specifications of each unit (size) to cost. In addition, the study also used the Chemical Engineering Plant Cost Index (CEPCI) to update the equipment cost to 2010 prices. For some equipment such as dryers, we have used scaling law equations relating the cost to size from similar examples found in the literature (Harrison *et al.*, 2003). Table 8.4 shows the total capital investment employed in this study.

2) Total operating cost

The total operating cost for the tea industry can be divided into three categories: direct (or variable) manufacturing costs, fixed manufacturing costs, and general expenses (Turton *et al.*, 2013). These costs are shown in Table 8.5. In this study, direct production costs represent approximately 68% of the total manufacturing cost. Fixed manufacturing costs and general expenses represent 21% and 11% of the total manufacturing cost, respectively. The annual operating expenses for the base case were estimated taking into account the variable operating costs (e.g. raw materials, utilities and maintenance), fixed operating expenses including labour wages and plant insurance. The raw materials cost consists of the cost of bought leaf from out growers, fertilizers, and packaging materials. The unit price of raw materials was determined by their market values in the year 2015. The cost of utilities consists of the cost of process steam, firewood, diesel and electricity and these are calculated according to the type and price of energy for each unit.

To estimate utility costs, the study assumes that firewood, electricity, process steam and diesel have prices of 11.41 US$/m^3, 0.043 US$/kWh, 60 US$/ton, and 15.93 US$/GJ, respectively. The prices for utilities used in this study are summarized in Table 8.6. The operating labour cost varies across tea companies and is estimated at 15% of total production costs. Variable costs related to field operations include tea cultivation and nursery establishment, pests and disease control, crop harvesting, timber plantations, replacement and development, and replacement and maintenance of tea fields.

Table 8.3: Equipment cost summary (factory capacity: 2 500 tons/year)

Equipment name	Capacity	Number required	Equipment cost per unit (US$)	Installed capital equipment cost (US$)
1. Triplex CTC machine		3	58 739.22	176 217.66
2. Rotor vane		3	9 930.91	29 792.73
3. VFBD Dryer	600 kg/h	3	63 000	189 000
4. Continuous oxidization (Fermentation) unit		3	42 500	127 500
5. Continuous withering machine		5	15 000	75 000
Total installed equipment				597 510.39

Table 8.4: Total capital investment (plant capacity: 2 500 tons/year)

	Parameter	Calculation	Value (US$)
A.	*Direct costs*		
A1.	Total purchased equipment cost (TPEC)		597 510.39
A2.	Total equipment installation	20% of TPEC	111 502.08
A3.	Piping	30% of TPEC	179 253.12
A4.	Instrumentation and controls	20% of TPEC	119 502.08
A5.	Insulation	3% of TPEC	17 925.31
A6.	Electrical equipment and materials	10% of TPEC	59 751.04
A7.	Building	30% of TPEC	179 253.12
A8.	Yard improvement	10% of TPEC	59 751.31
A9.	Auxiliary and service equipment	25% of TPEC	149 377.60
	Total installed cost (TIC)		1 481 825.77
	Indirect costs		
A10.	Engineering and supervision	15% of TIC	222 273.87
A11.	Construction	15% of TIC	222 273.87
A12.	Contractor's fees	3% of TIC	44 454.77
A13.	Contingency	7% of TIC	103 727.80
	Fixed capital investment (FCI)	TIC+	2 074 556
	Working capital (WC)	15% of FCI	311 183.41
	Total capital investment (TCI)	FCI+WC	2 385 739.49

Source: (Turton *et al.*, 2013)

Table 8.5: Total operating cost calculation (plant capacity: 2 500 tons/year)

	Parameter	Calculation	Value (US$)
I	Manufacturing cost		2 758 300.04
A.	Direct manufacturing costs (DMC)		1 490 158.59
A1.	Tea cultivation	21% of TPC	378 395.77
A2.	Maintenance	7% of TPC	126 131.92
A3.	Crop harvesting	13% of TPC	234 245.00
A4.	Timber plantations	1.7% of TPC	30 632.04
A5.	Replacement and development	1.3% of TPC	23 424.50
A6.	Replacement and maintenance	0.3% of TPC	5 405.65
A7.	Bought leaf	9% of TPC	162 169.92
A8.	Manufacturing	30% of TPC	529 754.08
	Variable costs		628 823.94
A9.	Operating labour	15% of TPC	270 282.69
A10.	Maintenance & repairs	6% of TPC	124 473.36
A11.	Direct supervisory and clerical labour	16% of TPC	40 542.40
A12.	Laboratory charges	15% of TPC	40 542.40
A13.	Operating supplies	15% of TPC	18 671.00
A14.	Patents & royalties	3% of TPC	62 236.68
A15.	Welfare	4% of TPC	72 075.39
B	Fixed manufacturing costs (FMC)		639 317.51
B1.	Depreciation	10% of FCI	207 455.51

B2.	Taxes	1.5% of FCI	31 118.34
B3.	Insurance	0.5% of FCI	10 372.78
B4.	Rent	1% of FCI	20 745.56
B5.	Capital repayment	10% of FCI	207 455.61
C	Plant overheads cost	50% of A9	
II	General expenses (GE)		351 486.94
D1.	Administration costs	25% of A9	67 570.67
D2.	Distribution and selling costs	10% of TPC	180 188.46
D3.	R&D costs	5% of TPC	103 727.80
III	Total production cost (TPC)	I+II	3 109 786.98
E	Unit product cost	TPC/production	1.33

Table 8.6: Utility cost for the plant operation

Utility	Price
Electricity	0.043 US$/kWh
Firewood	11.41 US$/$m^3$
Diesel	1.09 US$/litre
Steam	60 US$/ton

To evaluate the economic performance of the Malawian tea industry, the researcher opted to use the Net Present Value (NPV), which gives the financial achievement (profitability) of an investment over a certain period of time. In addition, other criteria such as ROI, BCR, and DCFROR have been calculated. To evaluate the profitability of base case study we assumed plant life to be 30 years after start up and that the construction of the plant finishes at the end of the first year. Annual maintenance and insurance expenditures in this industry are considered to be 5% and 0.5% of fixed capital investment (FCI), respectively. Working capital and salvage value of the plant at the end of the lifetime are set at 15% and 5% of the fixed capital investment (FCI) and capital cost, respectively. Future cash flows are discounted at a 10% annual rate and tax charges are set at 40%. The main economic inputs and assumptions adopted for economic analysis are presented in Table 8.7.

8.5.3 Economic results

In order to explore if an investment project for upgrading a tea production system is profitable for the base case company, the NPV, DCFROR, BCR, and ROI have been calculated, using a discount rate of 10% and an investment lifetime of 30 years. The average market price for tea produced in Malawi was taken to be US$1.6/kg of dried tea. This selling price is expected to rise following the corresponding increase in inflation from 2 to 10% over the lifetime. The results of the economic analysis of upgrading a tea production system are given in Table 8.8. The results of the economic analysis revealed that for the base case of the tea factory with a 2 500 ton capacity, the total capital investment is approximately US$2.4 million, where surprisingly, the majority of the investment comes from associated costs of installing the purchased equipment. Annual operating cost for the factory is estimated at US$3.1 million, which accounts for operating labour, maintenance cost, supervision cost, utilities cost and raw materials cost. The net present value (NPV) of the plant after a lifetime of 30 years would be US$3.2 million, with a discounted cash flow rate of return of 13.6% and return on investment of 56%. These values suggest that investing in new technology for tea production is profitable. The study did not find an economic analysis of a tea factory investment using software package for process evaluation in the open literature. However, the calculated IRR is below the 25% threshold for securing capital investment in new processing technology (Brown *et al.*, 2012).

Table 8.7: Economic analysis results of base case study firm 1

Parameter	Value
Factory size (tons/year)	2 500
Total capital investment (US$)	2 385 739
Variable operating costs (US$/year)	2 461 341
Fixed operating cost (US$/year)	627 701
Total production cost (US$/year)	3 109 787
Net Present Value (US$)	3 163 106
Discounted Cash Flow Rate of Return (%)	13.6
Return on Investment (%)	56
Benefit Cost Ratio	1.02

8.5.4 Sensitivity analysis

To evaluate the effect of economic parameters on the performance of the tea production system, sensitivity analyses were conducted for the various specified ranges of the input variables depicted in Table 8.2. The parameters analysed were capital investment, tea sales price, sales volume, discount rate, operating income, corporate tax, and revenue. These were varied by ±10, 20, and 30% of their original values as shown in Table 8.9. The discount rate was varied from 5% to 15%. The results of the sensitivity analysis on tea sales price are shown in Figures (8.10) and (8.11). The NPV changed significantly with the change in the selling price of made tea. The result indicated that for 10% increase in the selling price of tea, the NPV increased approximately $2,090,254 and vice versa. Therefore, the NPV has the highest sensitivity to changes in the selling price of tea. The results further show for tea selling price below US$1.5/kg, the cost of the investment project is not economically viable.

Results of this base case analysis suggest that NPV is very sensitive to the net revenues obtained from tea sales. Hence, the greater the revenues, the greater the NPV. Based on the model results, an increase of 10% in revenue results in an 8% increase in NPV. Variable costs per unit production of tea have a moderate impact on the NPV, with increases of 10% and 20% in variable costs resulting in 4% and 8% decrease in NPV respectively, and vice versa. NPV decreased by 0.72% and 2.2% when income tax was increased by 10% and 30% respectively. Conversely, NPV increased by 0.72% and 2.2% when income tax was decreased by 10% and 30% respectively. NPV also increased by 8% and 23% when the capital costs were reduced by 10% and 30% respectively, and vice versa. Results of this study clearly demonstrate that variable cost per unit and tax rate do not have a significant effect on profitability.

The sensitivity analysis of the NPV to changes in the discount rate is shown in Figure 8.1. The results in Figure 8.1 show that NPV decreases gradually when the discount rates increase. Compared with the NPV at 10% discount rate, if 15% nominal discount rate is applied, the change in NPV for the base study case will be 6%. If 5% discount rate is applied, the change in NPV for the base case study will be 7%. As a result, all the assumptions are good for investment: NPV>0, except in the case of changing tea sales price. The sensitivity analysis of the NPV to changes in unit selling price of made tea is also shown in Figure 8.3. The net present value increases as the market price of tea increases; if the tea selling price increases by 25%, the NPV and IRR values attained is $8,388,742 and 34.9% (from 13.6%), respectively. Results further show higher profitability of tea production with NPV and IRR reaching US$24, 718,853 and 100.4%, respectively.

Table 8.8: Parameter values used for sensitivity analysis

Variable	% of base value
Sales price (US$/kg)	-30 to +30%
Capital cost (US$)	-30 to +30%
Revenue (US$)	-30 to +30%
Variable cost per unit (US$/kg)	-30 to +30%
Tax rate (%)	-30 to +30%
Discount rate (%)	-30 to +30%
Real cost of capital (%)	5 to +30%
Sales volume (kg)	-30 to +19%
Operating income (US$)	-30 to +30%

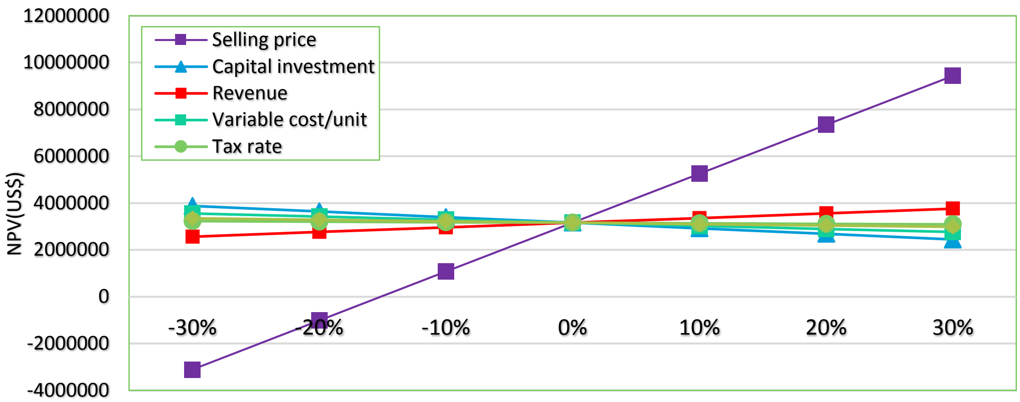


Figure 8.1: Sensitivity analysis of the NPV to economic parameters

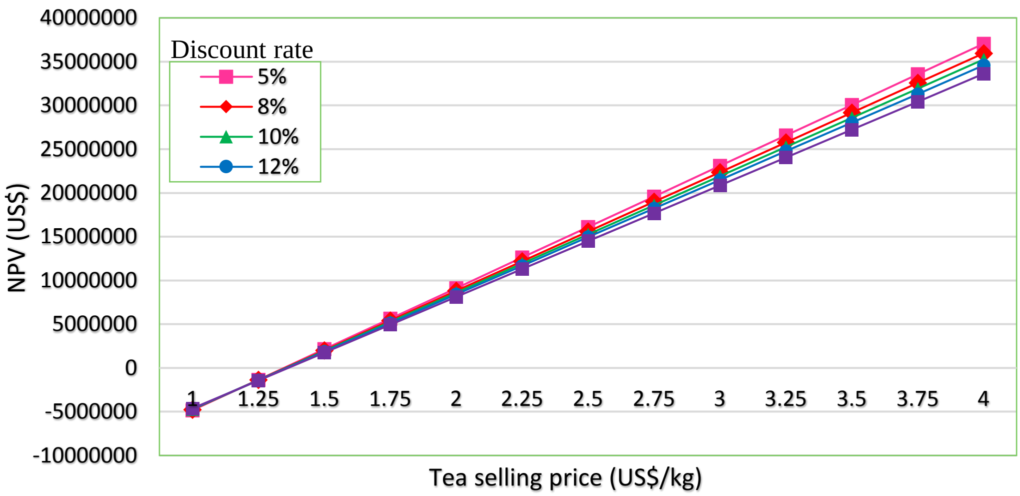


Figure 8.2: Sensitivity analysis of NPV to discount rates

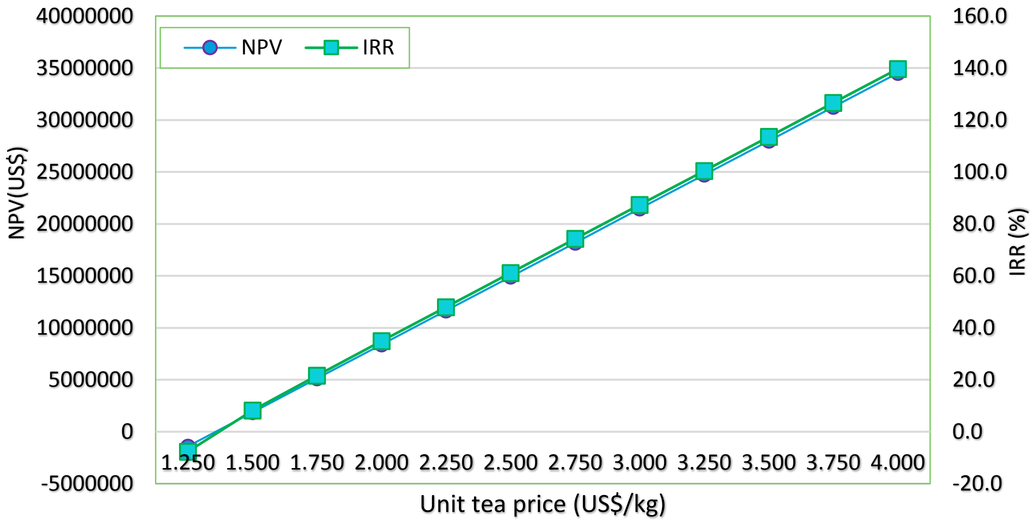


Figure 8.3: Sensitivity analysis of NPV due to changes on selling price

The sensitivity analysis of the NPV to changes in unit sales and real cost of capital is shown in Figure 8.1. The results in Figure 8.3 show that at 5% real cost of capital and with increases of 10% and 30% in unit sales, the NPV increased by between 64 and 192% compared to the base case scenario, respectively and vice versa. The results also showed that at 11% real cost of capital and with increases of 10% and 30% in unit sales, the NPV increased by between 67 and 200% compared to the base case scenario, respectively and vice versa. Similarly, at 15% real cost of capital and with increases of 10% and 30% in unit sales, the NPV increased by between 69 and 206% compared to the base case scenario, respectively and vice versa. At 19% real cost of capital and with increases of 10% and 30% in unit sales, the NPV increased by between 70 and 211% compared to the base case scenario, respectively and vice versa. The trends for NPV at lower and higher real cost of the capital mainly followed the trends in the NPV for the base case scenario. The results of this study indicate a higher NPV at 5% real cost of capital and a lower NPV at 19% real capital cost. There, NPV is highly sensitive to the amount of tea sold and the real capital cost.

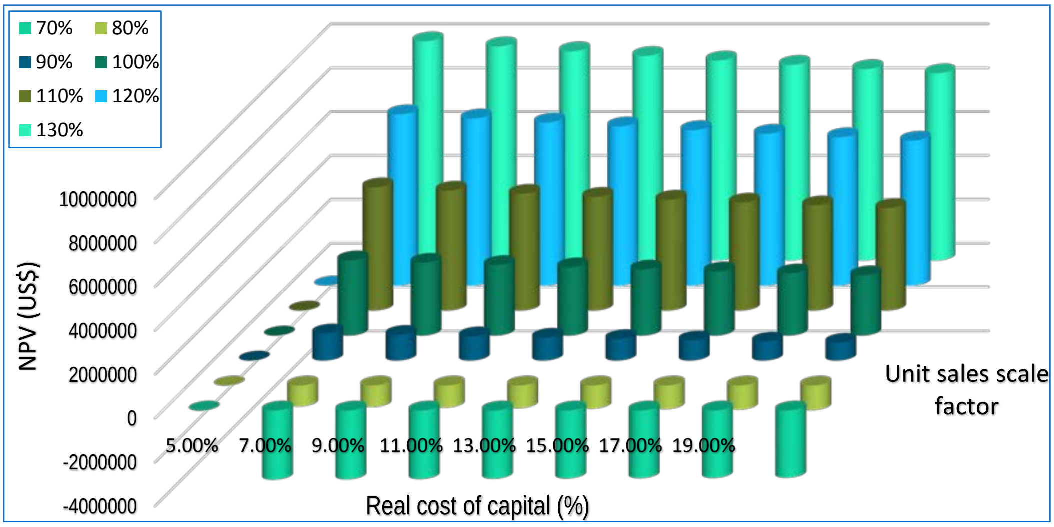


Figure 8.4: Effect of unit sales and real cost of capital on NPV

The sensitivity analysis of operating income (profit) and revenue is shown in Figure 8.2. The results indicated that the operating income of the base case study is particularly sensitive to changes in the amount of made tea sold. The volume of tea production has a large effect on the operating income and revenue, which increases with the increase in the amount of tea sold. The project would not be profitable for sales volume decrease of 10% or more. Thus, an investment like this is subject to some risk related to market conditions.

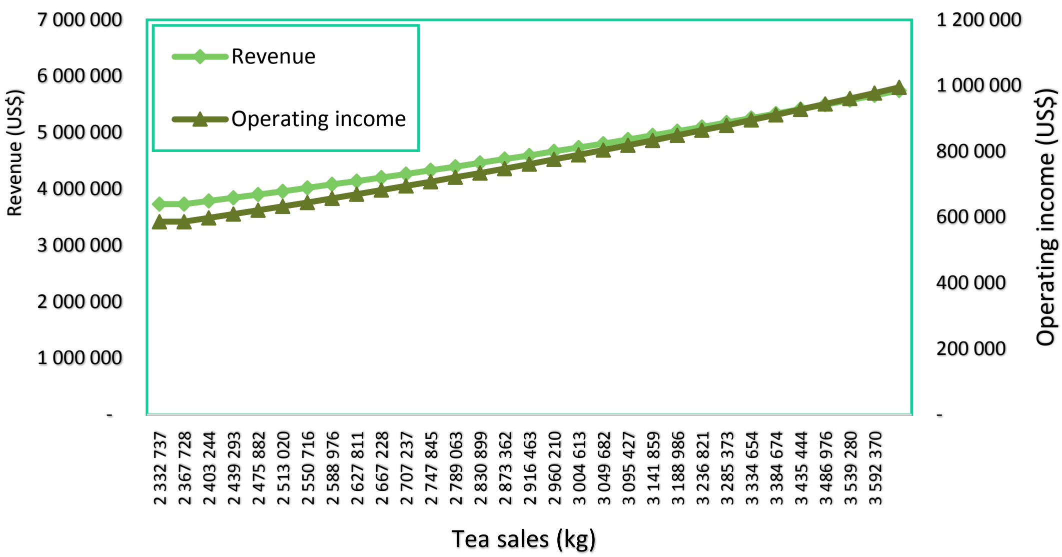


Figure 8.5: Sensitivity of revenue, operating income with tea sales

Table 8.9: Sensitivity analysis on (a) capital investment (b) unit selling price

Scenario	Capital investment (US$)	NPV (US$)	IRR (%)	ROI (%)	BCR
Base case	2 385 739	3 163 106	13.6	56	1.02
Reduction in capital investment					
S 30% reduction		3 878 828	23.3	123	
S 20% reduction		3 640 254	19.3	96	1.18
S10% reduction		3 401 680	16.2	74	
Increase in capital investment					
10% increase		2 924 532	11.5	42	0.95
20% increase		2 685 958	9.8	30	0.87
30% increase		2 447 384	8.3	20	0.79
100% increase		777 366	1.8	-22	
Tea selling price (US$/kg)		NPV	IRR	ROI	BCR
Base case	1.6	3 163 106	13.6	56	1.02
30% decrease		-3 107 657	-	10	-1.01
20% decrease		-1 017 403	-5.2	25	-0.33
10% decrease		1 072 852	4.8	41	0.35
Increase in tea selling price					
10% increase		5 253 360	22.2	72	1.70
20% increase		7 343 615	30.6	88	2.38
30% increase		9 433 869	39.1	103	3.05

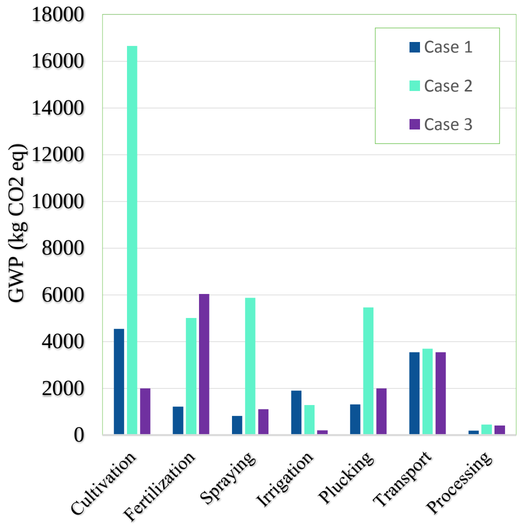
8.5.5 Environmental results using life cycle assessment

The environmental performance of the three case studies has been calculated following the ReCIPe 2008 impact assessment method. Details concerning the impact and damage categories, allocation procedures and calculation steps are presented by Goedkoop *et al.* (2013). The presentation aggregates inventory results in several impact categories. It identifies global warming (GWP), abiotic depletion potential (ADP), ozone depletion potential (ODP), terrestrial acidification potential (TAP), and freshwater eutrophication potential (FEP) as some of the categories. There are also marine eutrophication potential (MEP), terrestrial eutrophication potential (TEP), human toxicity potential (HTP), and photochemical oxidant creation potential (POCP). Finally, there are particulate matter formation (PMF), terrestrial ecotoxicity potential (TETP), freshwater aquatic ecotoxicity potential (FAETP), marine aquatic Ecotoxicity potential (MAETP), land use, and cumulative energy demand (CED).

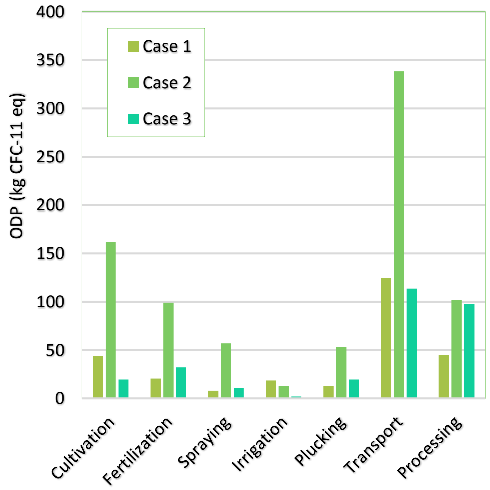
The environmental performance of the three base case study companies per impact category is given in Table 8.10. Figures 8.6a to Figure 8.6n also provides a comparative environmental analysis of the three representative cases based on ReCiPe method. The results obtained indicate that cumulative energy demand

(CED), global warming potential (GWP), marine aquatic ecotoxicity potential (MAETP), freshwater eutrophication potential (FEP), marine eutrophication potential (MEP), terrestrial eutrophication potential, human toxicity potential, and abiotic depletion potential (ADP) are the most significant environmental impacts associated with tea production in all three case studies. The results cannot be directly compared due to the differences in plant capacity, processing and age of machinery and equipment installed, and management systems. These results however, suggest an increase in the plant capacity results in increase in the total impact score.

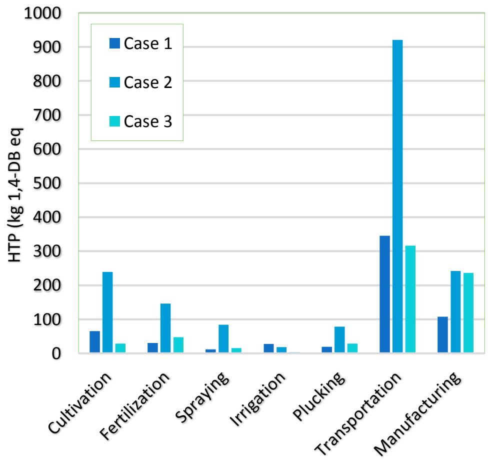
a) Global warming potential



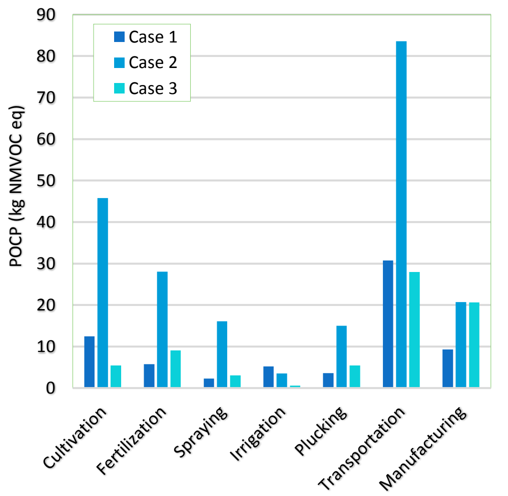
b) Ozone depletion potential



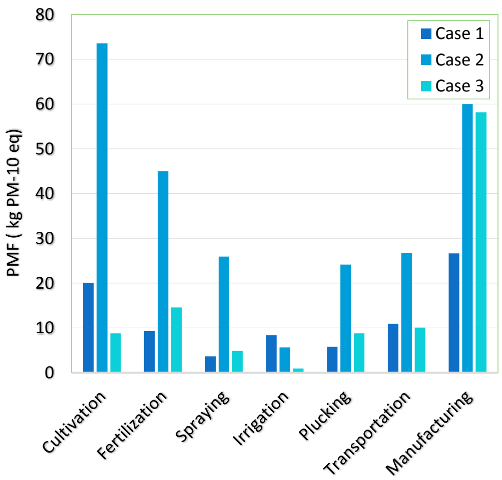
c) Human toxicity potential



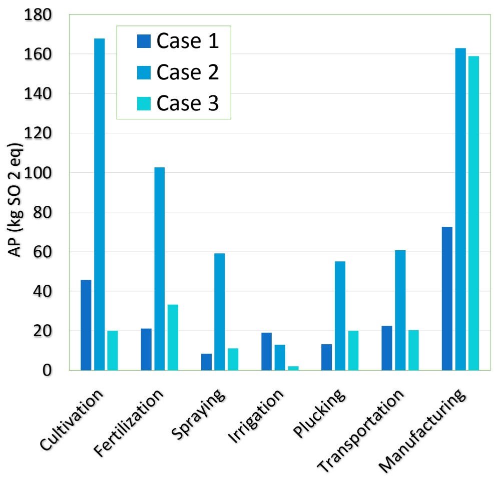
d) Photochemical oxidant creation



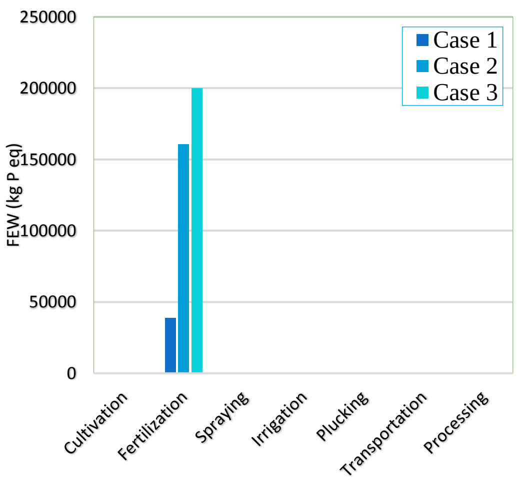
e) Particulate matter formation



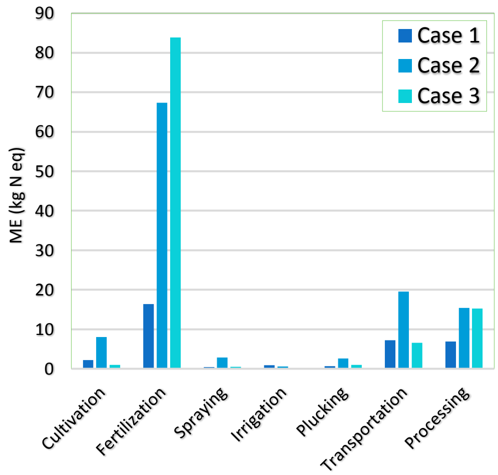
f) Acidification potential



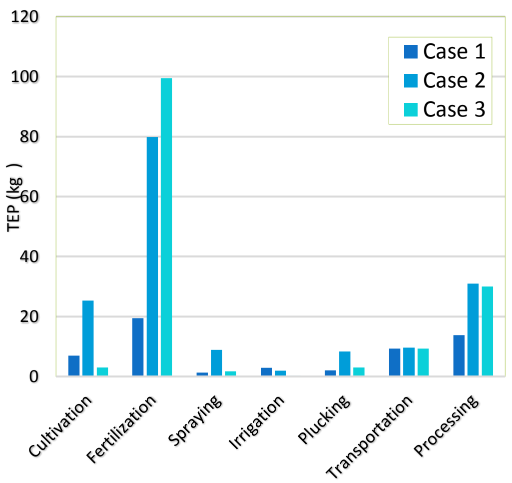
g) Freshwater eutrophication potential



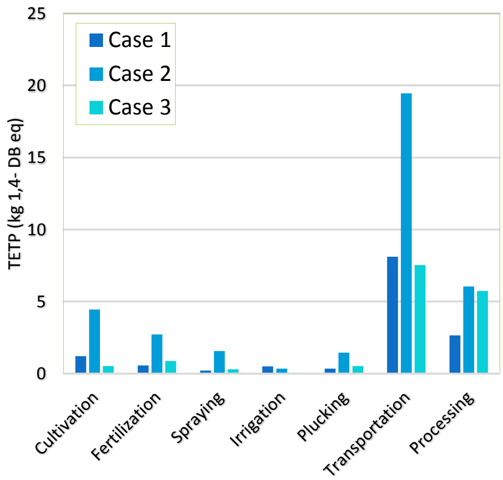
h) Marine eutrophication potential



i) Terrestrial eutrophication potential



j) Terrestrial ecotoxicity potential



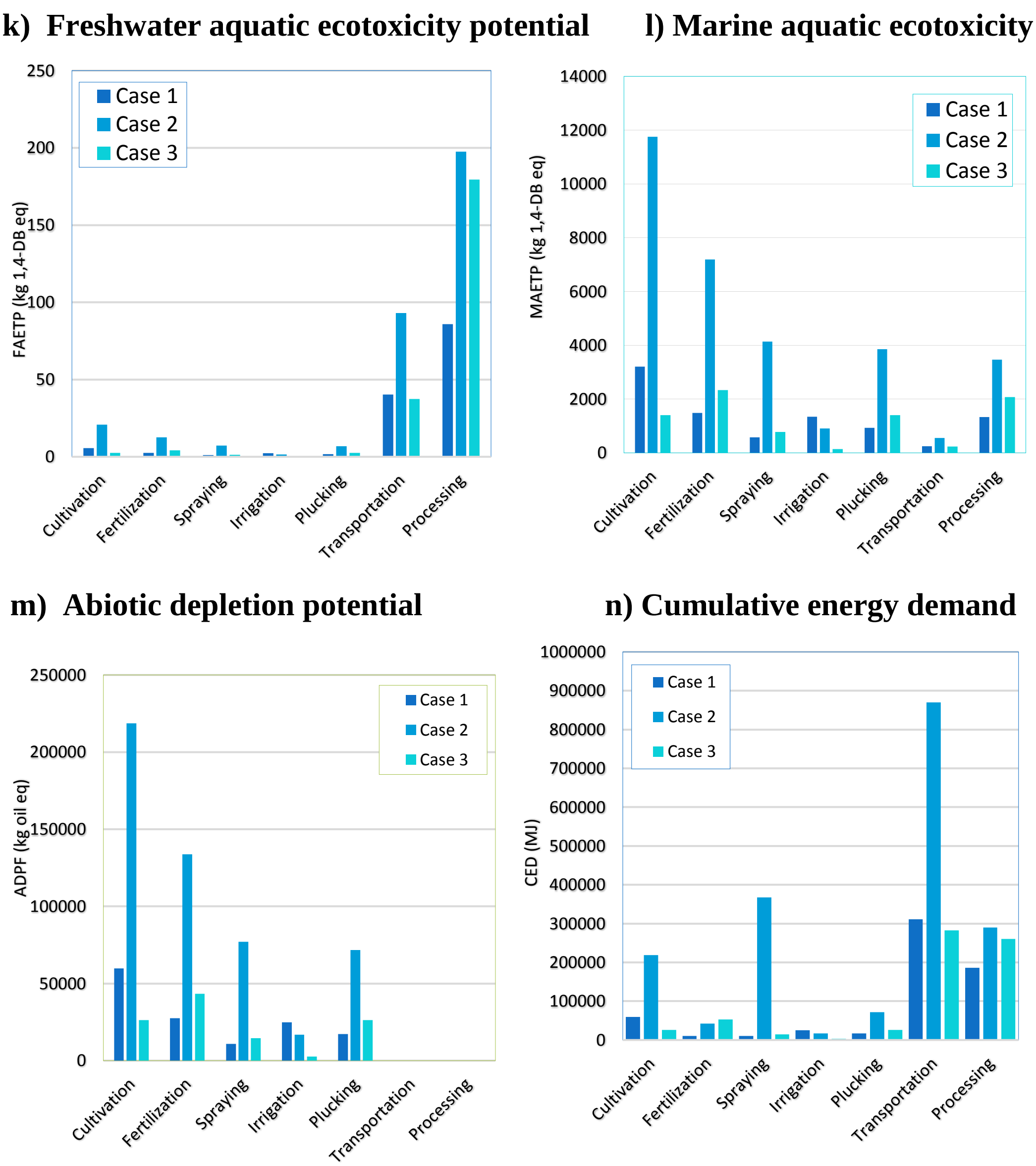


Figure 8.6: Characterization results for the production and processing of tea

The relative contributions of each life cycle stage studied to the overall environmental impacts are presented graphically in Figures 8.7, 8.8, and 8.9. The results show that the processing stage makes the largest contribution to the environmental impacts of ozone depletion, human toxicity, photochemical oxidant creation, acidification, eutrophication, and cumulative energy demand, with average contributions greater than 83%. The analysis revealed that combustion of biomass and diesel were the major cause of the environmental burdens in the tea processing stage. Results further revealed that application of chemical fertilizer and soil management such as lime and dolomite were a major cause of the environmental burdens. Therefore, improvement measures should focus on reducing biomass and fossil usage at factories as well as fertilizer use in tea fields.

Table 8.10 Characterization results for tea production

Impact categories	Unit	Total impact score		
		Case 1	Case 2	Case 3
Mid-point				
Global Warming Potential (GWP)	kg CO_2 eq	1 505 630	5 714 573	6 536 909
Ozone Depletion Potential (ODP)	kg CFC-11 eq	4 734	10 886	9 970
Terrestrial Acidification Potential (TAP)	kg SO_2 eq	7 590	17 307	16 186
Freshwater Eutrophication (FEP)	kg P eq	39 047	160 538	199 969
Marine Eutrophication Potential (MEP)	kg N eq	17 080	68 915	85 412
Terrestrial Eutrophication (TEP)	kg PO2 eq	21 743	83 971	103 406
Human Toxicity Potential (HTP)	kg 1,4 -DB eq	11 290	25 715	24 080
Photochemical Oxidant Creation (POCP)	kg NMVOC eq	9 361	20 928	20 676
Particulate Matter Formation (PMF)	kg PM10 eq	2 821	6 440	5 948
Terrestrial Ecotoxicity Potential (TETP)	kg 1,4 -DB eq	2 677	6 073	5 748
Freshwater Aquatic Ecotoxicity (FAETP)	kg 1,4 -DB eq	8 721	20 128	18 131
Marine Aquatic Ecotoxicity (MAETP)	kg 1,4 -DB eq	1 394 492	3 647 186	2 142 440
Abiotic depletion, elements (ADPE)	kg Sb eq	989 937	4 070 000	5 069 676
Abiotic depletion, fossil fuel (ADPF)	kg oil, eq	140 286	518 184	112 908
Cumulative Energy Demand (CED)	MJ	197015 922	333725 434	314 240 376
Non-renewable fossil	MJ	716 281	2 171 603	649 879
Non-renewable elements	MJ	10 348 668	42 837 858	52 997 724
Renewable (hydro)	MJ	21 068 213	21 068 213	21 068 213
Renewable, biomass	MJ	83 882 760	186647 760	186 647 760
Process energy	MJ	81 000 000	81 000 000	52 876 800
Solid waste				
Non-hazardous waste disposed	kg	15 862	26 002	12 356
End-point				
Damage to Human Health (HH)	DALY	1 522 844	5 753 125	6 573 802
Damage to Ecosystem Quality (EQ)	PDF *m^2 yr	1 495 667	4 008 436	2 575 609
Damage to Resource Availability (RA)	MJ surplus	1 130 223	4 588 184	5 182 584

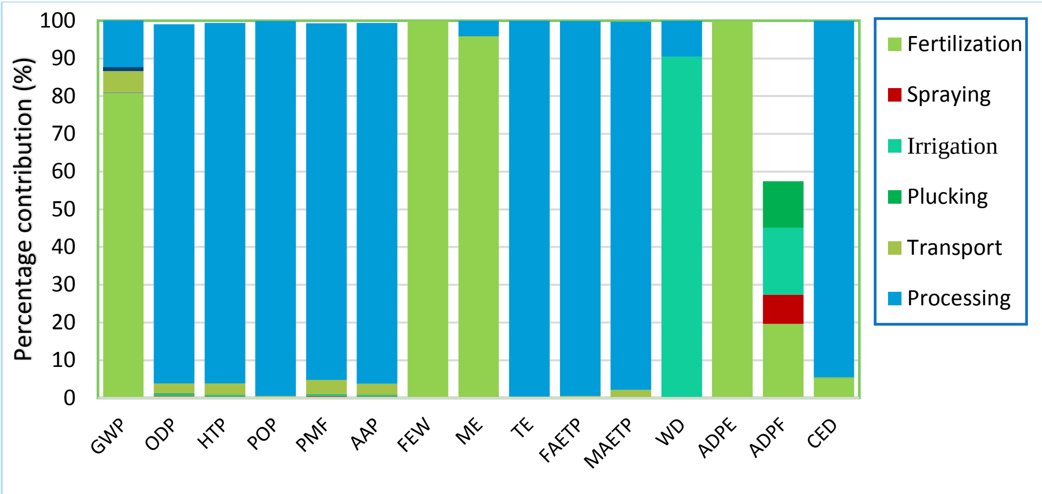


Figure 8.7: Contribution by different life cycle stages for case 1

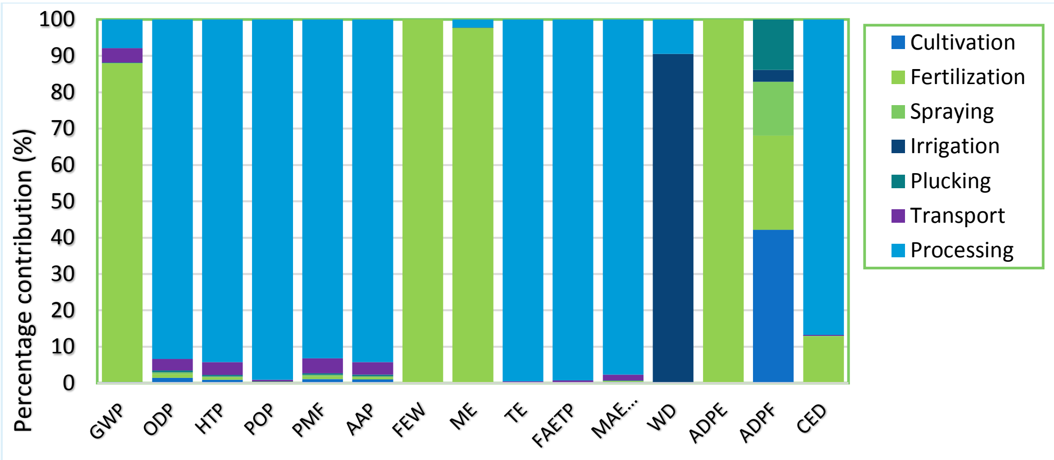


Figure 8.8: Contribution by different life cycle stages for case 2

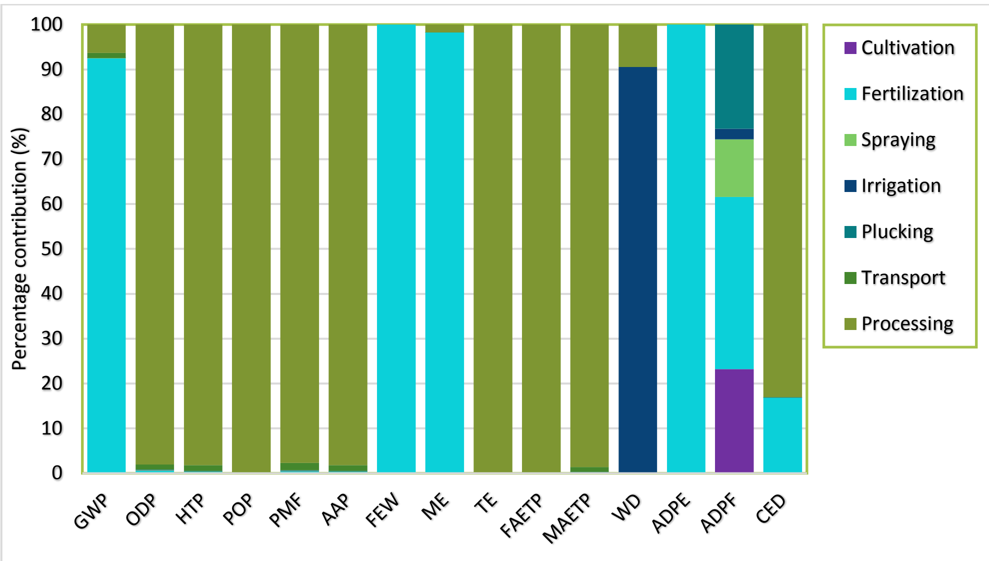


Figure 8.9: Contribution by different life cycle stages for case 3

The results of the life cycle impact assessment are shown in the following subsections for each category of impact.

(1) Global warming potential (GWP)

This impact category estimates the contribution of the functional unit to global warming. To calculate the global warming potential for a 100 year time horizon, the study used characterization factors developed by the UN Intergovernmental Panel on Climate Change (IPCC). The result from the life cycle assessment revealed that tea production contributed an average of 2809 kg CO_2 equivalent per ha (0.64 kg $CO_{2\ eq}$/kg dried tea). The GWP emissions varied from 2579 to 3042 kg CO_2/ha (0.21-0.91kg $CO_{2\ eq}$/kg dried tea). The analysis revealed that crop fertilization and manufacturing were the main contributors to the GWP, accounting for 87% and 9% of the total emissions. CO_2 was the largest contributor to global warming, followed by N_2O and CH_4. The main source of emissions is CO_2 from firewood and diesel combustion in the different agricultural operations as well as that from urea, lime and dolomite application.

(2) Abiotic depletion potential (ADP Elements and ADP Fossil)

The impact category abiotic depletion relates to the extraction of minerals and fossil fuels. Results showed the mean value for abiotic depletion to be 2000 kg Sb_{eq}/ha [0.47 kg Sb_{eq}/kg dried tea] and 194 kg oil_{eq}/ha [0.04 kg oil eq/kg dried tea], with case 1 being the best and case 3 the worst. The depletion of elements is largely due to the cultivation and growing of tea, which is associated with heavy application of nitrogen, phosphate, and potassium fertilizers. The major contributors to fossil depletion are the fuel used in the agricultural machinery for cultivation, spraying, fertilizing, and processing. The contribution from irrigation and transport related activities are insignificant.

(3) Acidification potential (AP)

Tea production contributes to acidification, which often results in a wide variety of impacts on soil, ground, surface waters, biological organisms, and systems. Major pollutants contributing to acidification are NH_3, NOx and SO_2. In this study, acidification potential was calculated using characterization factors provided by Huijbregts 1992. The total contribution of acidification varied from 6.38 to 15.33 kg $SO_{2\ eq}$/ha (0.0011 to 0.0024 kg $SO_{2\ eq}$/kg dried tea), with a mean of 10.07 kg/ha (0.002 kg $SO_{2\ eq}$/kg dried tea). The manufacturing stage accounted for 96% of the impact to acidification. Combustion of firewood and diesel for steam and stand-by power generation, respectively, were the main sources of NH_3, NOx and SO_2 emissions.

(4) Eutrophication potential (EP)

Eutrophication covers all potential impacts of high environmental levels of macronutrients such as nitrogen and phosphorus. Characterization factors used in the calculation were taken from Guinee *et al* 2002. The total contribution to freshwater eutrophication was 78.88 kg P eq/ha (0.0186 kg P eq/kg dried tea). The total contribution to marine eutrophication varied from 33.7 to 34.5 kg N eq/ha

(0.0024 to 0.012 kg N eq/kg dried tea), with a mean value of 34.02 kg N eq/ha (0.008 kg N eq/kg dried tea). The values for terrestrial eutrophication varies from 40.8 to 43.9 kg N eq/ha (0.003 to 0.0144 kg N eq/kg dried tea), with a mean value of 42 kg N eq/ha (0.010 kg N eq/kg dried tea). Fertilizer application was the largest source of freshwater eutrophication (100%), marine eutrophication (97.3%), while processing contributed 99.6% of terrestrial eutrophication. The application of mineral fertilizer was the main source of NO_3- emissions. NOx and NH_3 depositions represent the principal contributors to the terrestrial eutrophication.

(5) Photochemical oxidants creation potential (POCP)

The combustion of fuel during tea production processes and crop transportation causes emissions of VOC, CO, CH_4 and NOx, which are considered to be tropospheric ozone precursors. The characterization factors used in the calculation of the POCP were taken from Hauschild and Wenzel (1998), Heijungs *et al* (1992), and Goedkoop (2000). Total contribution to POCP varied from 8.16 to 18.9 kg NMVOC $_{eq}$/ha (0.0013 to 0.003 kg NMVOC eq/kg dried tea), with a mean value of 12.45 kg NMVOC $_{eq}$/ha (0.0024 kg NMVOC eq/kg dried tea). Processing stage was the largest contributor to POCP, accounting for 99.5% of total contribution due to firewood and diesel combustion. The contribution from cultivation, irrigation, spraying and transportation is insignificant.

(6) Ozone depletion potential (ODP)

This impact category is mainly a result of processing tea at the factories, which produces much of the carbon monoxide responsible for depleting the ozone. Tea processing accounts for approximately 95% contribution to this category. The ODP ranges from 3.9 to 9.6 kg CFC-11 eq/ha (0.0007 to 0.0015 kg CFC-11 eq/kg dried tea), with an average of 6.3 kg CFC-11 eq/ha (0.0012 kg CFC-11 eq/kg dried tea). The main contributors are halons emitted during crop transportation as well as emissions from diesel used in the machinery during cultivation and processing.

(7) Human toxicity potential (HTP)

The scores for the human toxicity impact category is highly dominated by the processing stage followed by fertilization and transportation, with contributions of 96%, 1.31% and 0.3% respectively. The HTP ranges from 9.5 to 23 kg CFC-11 eq/ha (0.0016 to 0.0036 kg CFC-11 eq/kg dried tea), with an average of 15 kg CFC-11 eq/ha (0.003 kg CFC-11 eq/kg dried tea). Processing and fertilization activities are the main responsible activities, with air borne emissions of polycyclic aromatic hydrocarbons and chromium VI from combustion of fossil fuels being the principal causal agents. The use of pesticides also contributes to human toxicity.

(8) Ecotoxicity potentials (FAETP, MAETP, and TETP)

The toxic elements in this study were heavy metals and pesticides. Characterization factors used in the calculation of FAETP, MAETP, and TETP were taken from Guinee *et al*. 2002. The total contribution to freshwater aquatic ecotoxicity ranged from 7.2 to 17.6 kg 1,4 -DB $_{eq}$/ha (0.0012 to 0.0028 kg 1,4 -DB $_{eq}$//kg dried tea), with an average of 11.55 kg 1,4 -DB $_{eq}$/ha (0.0022 kg 1,4 -DB $_{eq}$/kg made tea). The total contribution to marine aquatic ecotoxicity varied from 845 to 2817 kg 1,4 -DB $_{eq}$/ha (0.195 to 0.51 kg 1,4 -DB $_{eq}$/kg dried tea), with a mean value of 1818 kg 1,4 -DB $_{eq}$/ha (0.334 kg 1,4 -DB $_{eq}$/kg dried tea). The values for terrestrial ecotoxicity varied from 2.27 to 5.41 kg 1,4 -DB $_{eq}$/ha (0.0004 to 0.0008 kg 1,4 -DB $_{eq}$/kg dried tea), with a mean value of 3.55 kg 1,4 -DB $_{eq}$/ha (0.0007 kg 1,4 -DB $_{eq}$/kg dried tea). Tea processing, fertilization and spraying are the main contributors to this impact. This is mainly due to the emission pesticide used for tea growing and heavy metals from use of chemical fertilizers. The use of diesel in cultivation, transportation, irrigation and manufacturing activities was also a source of heavy metals.

(9) Cumulative Energy Demand (CED)

The impact category cumulative energy demand represents the direct and indirect energy use (in units of MJ) throughout the life cycle, including the energy consumed during extraction, manufacturing and disposal of the raw material and auxiliary materials (Frischknecht *et al.*, 1998). The total CED is composed of the fossil cumulative energy demand (i.e. from hard coal, lignite, peat, natural gas, and crude oil) and the CED of nuclear, biomass, water, wind, and solar energy in the life cycle. Energy use was calculated using lower heating values taken from the ecoinvent database. The CED varied from 123 961 to 398 011 MJ/ha (27.51 to 46.6 MJ/kg dried tea), with an average of 228 652 MJ/ha (39.3 MJ/kg dried tea). The manufacturing step is the most important consumer of energy, followed by fertilization, with contributions of 88% and 12% respectively.

Table 8.11: Summary results for environmental impacts of tea production

Impact category	**Potential environmental impact**	
	per kg of tea	per hectare
Global Warming Potential (kg CO2 eq)	0.6403	2809.43
Ozone Depletion Potential (kg CFC-11 eq)	0.0012	6.28
Acidification Potential (kg SO2 eq)	0.0019	10.07
Freshwater Eutrophication Potential (kg P eq)	0.0186	78.88
Marine Eutrophication Potential (kg N eq)	0.0080	34.02
Terrestrial Eutrophication Potential (kg PO2 eq)	0.0097	41.99
Human Toxicity Potential (kg 1,4 -DB eq)	0.0028	14.98
Photochemical Oxidant Creation Potential (kg NMVOC eq)	0.0024	12.45
Particulate Matter Formation (kg PM10 eq)	0.0007	3.74
Terrestrial Ecotoxicity Potential (kg 1,4 -DB eq)	0.0007	3.55
Freshwater Aquatic Ecotoxicity Potential (kg 1,4 -DB eq)	0.0022	11.55
Marine Aquatic Ecotoxicity Potential (kg 1,4 -DB eq)	0.3344	1818.14
Abiotic Depletion Potential, Elements (kg Sb eq)	0.4715	1999.87
Abiotic Depletion Potential, Fossils (kg oil, eq)	0.0359	194.19
Cumulative Energy Demand (MJ)	39.33	228651.

Waste Production (kg)	0.0025	16.57
Human Health (DALY)	0.6446	2832.19
Ecosystem Quality (PDF*m2*yr)	0.3760	2002.40
Resource Availability (MJ surplus)	0.5074	2194.06

8.6 Social life cycle assessment

The social performance of the three case study companies have been evaluated based on UNEP/SETAC[5] guidelines for social life cycle assessment of products and includes four main phases, similar to LCA: goal and scope definition, life cycle inventory assessment, and life cycle interpretation (Benoît & Mazijn, 2009a). This study assessed social issues that may affect different stakeholders positively or negatively in the Malawian tea industry. The study in particular, assessed the manner in which the case study companies relate to the five main stakeholder groups (workers, consumers, local community, society, and value chain actors) described in the guidelines. The stakeholder categories, impact categories, impact subcategories, subcategories, inventory indicators, and social impact criteria, adopted in this study are based on UNEP/SETAC. Moreover, this study paid particular attention to mid-point categories since the use of end points implies the aggregation of results, which in turn reduces transparency and increases uncertainty. Furthermore, in the frame of social life cycle assessment (S-LCA), only one end point category exists: human well-being. The impact categories considered in this study include: human rights, working conditions, health and safety, socio-economic repercussions, cultural heritage, and governance.

8.6.1 Goal and scope definition

The goal of this S-LCA is to provide awareness of the socio-economic impacts of tea production so that stakeholders in the industry can make informed decisions at various stages of product life cycle. This part of the study aimed to assess the social impacts of tea production processes in the Malawian tea industry. Furthermore, the study aimed at identifying social hot spots in the life cycle of tea and it derives recommendations at the enterprise level in order to improve the sustainable performance of the tea industry. This scope of the study is the Malawian tea industry, and covered agricultural and manufacturing activities of the industry. The focus of the study was on the social effects of tea production processes on workers, society and local communities where production takes place. The study also identified the affected stakeholder groups, impact categories, subcategories and indicators to be included in the analysis based on the goal of this study. In addition, the criterion for scoring the performance of the case study companies on each indicator was determined in preparation for the life cycle inventory.

[5] A cooperation between the United Nations Environmental Programme (UNEP) and the Society of Environmental Toxicology and Chemistry (SETAC)

8.6.2 System boundary

The system boundary of the S-LCA for tea production included life cycle stages of cultivation, production, plucking (harvesting), transportation, and processing. For purposes of simplification, the S-LCA did not cover downstream activities such as distribution and use phases of made tea. In addition, impacts and considerations with the consuming nations were not investigated. Furthermore, the research did not cover tea industries outside Malawi. The functional unit used in this study was 1 kg of made tea.

8.6.3 Social life cycle inventory analysis

Data on social impacts of the production of made tea were collected for the subcategories defined in the UNEP-SETAC guidelines on S-LCA. The stakeholder categories considered were employees (workers), local community, and society. The stakeholder categories related to consumers and value chain actors were excluded from the scope of the study. Data collection activities took place between January 2014 and December 2015. Data was collected from the three studied tea companies. The inventory data used in this study is qualitative, semi-quantitative and quantitative in nature, and were collected by means of questionnaire, face-to-face interviews and observation. The social impacts were calculated by means of the MOISAT tool and based on the inventory data for all the studied tea companies.

8.6.4 Social life cycle impact assessment (S-LCIA)

In order to assess the social impacts of tea production, an impact assessment method was developed and applied in the study. The method assessed each subcategory with a colour scale ranging from green (good performance/positive impact), yellow (rather poor performance/negative impact) to red (very poor performance/very negative impact). Orange and red nuances showed social hot spots. There are six steps in performing an E-LCA and these include definition of impact categories, classification, characterization, normalization, grouping and weighting. S-LCA follows the same framework as E-LCA, but focuses on social and socio-economic aspects. The first step was classification in which we identified stakeholder groups in accordance with UNEP-SETAC recommendations. Three out of the five stakeholders were considered as they were found to be relevant to this study. For each stakeholder group, the most relevant categories, subcategories, and indicators were selected. The second step consisted of an inventory analysis of data gathered through the questionnaire and face-to face interviews conducted in the studied tea companies as well as from the open literature. The third step involved the characterization of inventory data with a view to evaluate impacts of tea production. To perform the characterization, this study adopted the quantitative method, which is based on scoring. The results obtainable from the approach provide a platform for comparison with future studies.

To conduct an impact assessment based on the preferences and perceptions of stakeholders, the Analytic Hierarchy Process (AHP) was conducted with the involvement of relevant stakeholders in the area. The researcher conducted a survey involving a panel of experts and decision-makers in the tea industry in Malawi. The panel consisted of representatives from academia, social/environmental activists, members from non-governmental organizations, and governmental agencies with relevance to the tea industry. A weighting process was performed using a questionnaire, which allowed experts to assign direct ranking on every criterion and impact category according to their importance. A total of eight experts were recruited to participate in this study. Finally, the weighting of categories, subcategories, and indicators was implemented in MOISAT.

8.6.5 Social life cycle assessment results

Table 8.12 presents results obtained from the expert evaluation of criteria and impact category for the tea industry in Malawi. Results of the S-LCA clearly demonstrate that the experts ascribe the greatest local priority to human rights (0.4972) followed by working conditions (0.2486), cultural heritage (0.0994) and social-economic repercussions (0.0994), and the lowest weight in this category was scored by governance. The maximum eigenvalue was 5.000, which results in a consistency index (CI) value of 0.0000. The consistency ratio (CR) was calculated as 0.0000 and found to be acceptable and the judgments were undoubtedly consistent. The results of issues on each impact category will be discussed in the following subsections.

(1) Human rights

The social impact of tea production on the worker was evaluated in terms of human rights and working conditions. The study revealed violation of human rights issues in all three cases; in terms of employment of forced labour, gender discrimination, and employment of child labour. Compared to working hours in the formal private sector (48 hours/week), factory workers in the studied enterprises perform between 60 and 72 hours/week and thus exceed the threshold of 56 hours/week, including overtime work, as defined by the International Labour Organization (ILO) on Working Hours (ILO,1995). Discrimination and sexual abuse was reportedly prevalent in the studied organizations. Women were coerced into sexual relationships with their superiors, in exchange for favours such as better payment and promotion, or as a precondition for employment. The number of women in senior positions was also reported to be low. There were no occurrences of child labour in the studied enterprises. However, the assertion that child labour in the Malawian tea industry has been eradicated is questionable.

(2) Working conditions

Working conditions were also found to be hostile and unsatisfactory. The issues regarding working conditions is strongly correlated to situations where many of the jobs created in tea plantations and factories are for seasonal and casual labour, which is particularly vulnerable to low wages, lack of job security, and minimum legal protection. The minimum salary/wage payment for workers in all the case study enterprises was determined to be US$1.13 (MWK850)/day which was below the living wage of MWK1193 (US$1.59), and therefore, fails to provide the worker and the family with a decent living (Anker & Anker, 2014).

(3) Cultural heritage

The impact of tea production on the local community was assessed in terms of community engagement, safe and secure living conditions, and access to material resources. Results of the study indicated that each of the case study companies performs some corporate social responsibilities in their neighbourhood. Case 2 reported to have carried out a number of community based projects such as construction of 10 pit latrines, renovation of school blocks, community halls, farm inputs, provides malaria drugs to the district hospital. The company has provided cash donations to police, community based organizations, churches, paid school fees for some students; as well as provision of nutritional porridge and mid-day meals to children. The company also provides mother based programs and operates a clinic benefiting about 2 792 people in the surrounding villages. Interview results also showed that as a result of running maternity clinics, the infant mortality rate has reduced from 0.85% in the year 2010 to 0.20% in 2014, among the lowest in the district.

Table 8.12: Social impact categories, criteria, and their weights

Impact Categories	Weight	Subcategories	Label	Weight	Overall weight	Stakeholders
Human rights	0.4972	Free from the employment of child labour	HR_1	0.0882	0.0439	Workers
		Free from the employment of forced labour	HR_2	0.6687	0.3325	Workers
		Equal opportunities, free from discrimination	HR_3	0.2431	0.1209	Workers
		Sum		1.0000		
Working conditions	0.2486	Freedom of association and collective bargaining	WC_1	0.4972	0.1236	Workers
		Fair salary	WC_2	0.2486	0.0618	Workers
		Decent working hours	WC_3	0.0994	0.0247	Workers
		Occupational health and safety	WC_4	0.0994	0.0247	Workers
		Social benefit	WC_5	0.0552	0.0137	Workers
		Sum		1.0000		
Cultural heritage	0.0994	Land acquisition, delocalization, migration	CH_1	0.2207	0.0219	Local community
		Respect on customary right of indigenous people	CH_3	0.1047	0.0104	Local community
		Community engagement	CH_4	0.1470	0.0146	Local community
		Safe and healthy living conditions	CH_5	0.0643	0.0064	Local community
		Access to material resources	CH_6	0.0914	0.0091	Local community
		Access to non - material resources	CH_7	0.0198	0.0020	Local community
		Transparency on social/environmental issues	CH_8	0.1345	0.0134	Local community
		Sum		1.000		

Socio-economic repercussions	0.0994	Contribution to local employment	SE_1	0.3061	0.0304	Society
		Contribution to economic development	SE_2	0.3050	0.0303	Society
		Food security	SE_3	0.1708	0.0170	Society
		Horizontal conflict	SE_4	0.1222	0.0122	Society
		Transfer of technology and knowledge	SE_5	0.0959	0.0095	Society
		Sum		1.0000		
Governance	0.0552	Public commitments to sustainability	G_1	0.6000	0.0331	Value chain actors
		Fair competition	G_2	0.2000	0.0110	Value chain actors
		Free from corruption	G_3	0.2000	0.0110	Value chain actors
	1.0000	Sum		1.0000	0.9783	

Finally, the company also runs ambulance services – transporting patients from surrounding villages to the district hospital, with an average travelled distance of 5,000 km per month. Additionally, the company annually employs between 5 000 and 6000 people, 1 600 of these being women. However, tea production activities of the studied cases contribute to negative impact on the cultural heritage of the people as they infringe on the local communities' cultural practices, particularly with reference to sexual abuse by some employers that go unreported due to cultural beliefs.

(4) Socio-economic repercussions

The impact of tea production on society was assessed with respect to the firm's contribution to local employment and economic development. The results of the study clearly demonstrate that the case study firms have brought positive socio-economic impacts to the society, such as their contribution to local employment and economic development. The experts weighting for the two subcategories were at 0.3061 and 0.3050 respectively. Findings of the study also suggested that society does not view the tea companies as a threat on social cohesion or horizontal conflict, and food security.

Table 8.13: Hierarchical structure with weights for social assessment

Stakeholder	Weight	Indicator	Weight	Overall weight
Workers	0.5714	Child labour	0.1748	0.0999
		Forced labour	0.0662	0.0378
		Wages/Fair salary	0.1783	0.1019
		Working hours	0.0193	0.0110
		Equal opportunities/Discrimination	0.0356	0.0204
		Health and safety	0.0449	0.0257
		Social benefits	0.1798	0.1028
		Freedom of association and collective bargaining	0.3011	0.1721
		Sum	1.000	

Local community	0.1429	Access to material resources		0.3061	0.0437
		Respect to indigenous rights		0.3050	0.0436
		Safe and healthy living conditions		0.1708	0.0244
		Local employment		0.1222	0.0175
		Migration		0.0959	0.0137
			Sum	1.0000	
Society	0.2857	Technology development		0.2000	0.0571
		Contribution to economic development		0.6000	0.1714
		Public commitment to sustainability		0.2000	0.0571
			Sum	1.0000	
	1.0000				1.0000

Table 8.14: Comparative results of the performance of the case study firms

Stakeholder	Indicator	Case 1	Case 2	Case 3
Workers	Child labour (under 18 years)	no	no	no
	Forced labour	no	no	no
	Wages/Fair salary	no	no	no
	Working hours	yes	yes	yes
	Equal opportunities/Discrimination	no	no	yes
	Health and safety	yes	yes	no
	Social benefits (medical care, sickness allowance)	yes	no	no
	Freedom of association and collective bargaining	yes	yes	yes
Local community	Access to material resources	yes	yes	no
	Respect to indigenous rights	yes	yes	yes
	Safe and healthy living conditions	no	no	no
	Local employment	yes	yes	yes
	Migration			
Society	Technology development	no	no	no
	Contribution to economic development	yes	yes	yes
	Public commitment to sustainability	yes	yes	no

Table 8.15: Stakeholders, subcategories and their weights

Stakeholder categories	Subcategories	Cultivation	Spraying	Plucking	Transportation	Processing
Workers	Child labour					
	Forced labour					
	Wages/Fair salary					
	Working hours					
	Discrimination					
	Health and safety					
	Social benefits					
	Freedom of association and					

	collective bargaining	
Local community	Access to material resources	
	Respect to indigenous rights	
	Safe and healthy living conditions	
	Secure living conditions	
	Local employment	
	Migration	
	Community engagement	
Society	Technology development	
	Contribution to economic development	
	Public commitment to sustainability issues	
	Prevention & mitigation of conflicts	
	Corruption	

8.7 Multi-objective optimization: evaluation and results

In this section, experimental studies are conducted to verify the performance of the proposed multi-objective optimization algorithm. Results of the experimental as well as real-life industrial applications of the model are discussed.

8.7.1 Benchmark test problems

In order to evaluate the performance of the MOISAT, three standard benchmark test functions, namely Kursawe (KUR), BNH and ZDT3 have been used for experimentation. These functions were selected because they are amongst the popular set of test functions for benchmarking the performance of multi-objective optimization problems. In addition, each of these test functions contains a particular feature that is representative of a real-world optimization problem that could cause difficulty in converging to the Pareto optimal front. The descriptions of the test problems are given in Table 8.16.

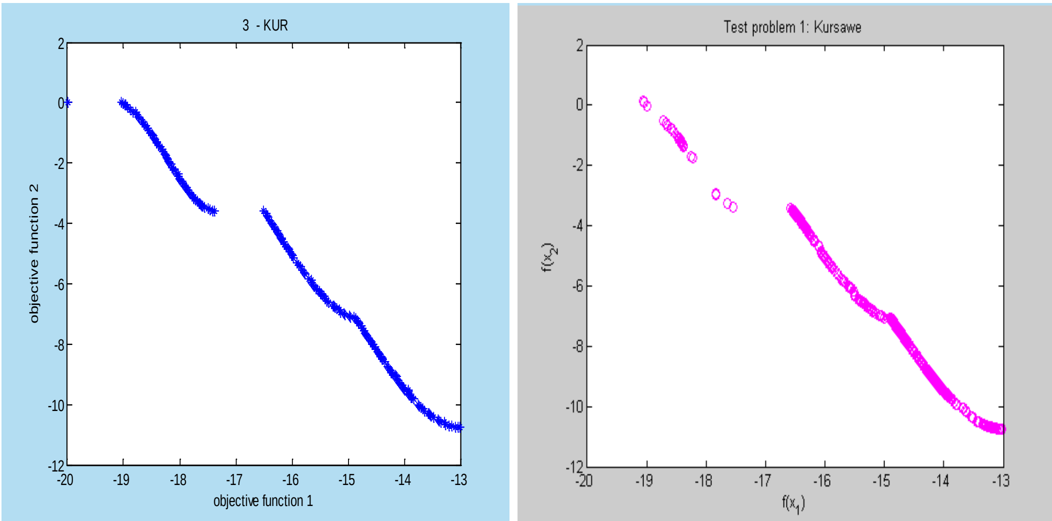
Table 8.16: Constrained and unconstrained test problems used in this study

Test problem	Variable bounds	Objective functions (minimize)	Constraints
BNH	$x_1 \in [0,5]$	$f_1(x) = 4x_1^2 + 4y_1^2$	$c_1(x) = (x_1 - 5)^2 + x_2^2 \leq 25$
	$x_2 \in [0,3]$	$f_2(x) = (x_1 - 5)^2 + (x_2 - 5)^2$	$c_2(x) = (x_1 - 8)^2 + (x_2 - 3)^2 \geq 7.7$
KUR	$x_i \in [-5,5]$	$f_1(x_1,x_2,x_3) = \sum_{i=1}^{2}\left(-10\, exp\left(-0.2\sqrt{x_i^2 + x_{i+1}^2}\right)\right)$	
	$\forall_i = 1,..,n$	$f_2(x_1,x_2,x_3) = \sum_{i=1}^{n}(\lvert x_i\rvert^{0.8} + 5\, sinx_i^3)$	
ZDT3	$x_i \in [0,1]$	$f_1(x) = x_1$ $f_2(x) = g(x)\left[1 - \sqrt{\frac{x_i}{g(x)}} - \frac{x_i}{g(x)}\sin(10\pi x_1)\right]$	$g(x) = 1 + 9\left(\sum_{i=2}^{n} x_i\right)/(n-1)$

The first test problem (KUR) has three decision variables and two objective functions, with the variables in the allowed range of -5 to 5. The Pareto optimal front is discontinuous, having three sets of non-dominated solutions as well as concave and convex search space. The second test problem (BNH) is a multi-objective optimization problem, with two constraints and two variables. The search space of this problem is also convex. The third test problem (ZDT3) is a multi-objective optimization problem, which adds a discreteness feature to the front and has a Pareto-optimal front disconnected, consisting of several non-contiguous convex parts. The introduction of the sine function causes discontinuities in the Pareto optimal front, but not in the decision variable space. Detailed descriptions of these test problems can be found in Kursawe (1991), Binh and Korn (1997), and Zitler *et al.* (2000).

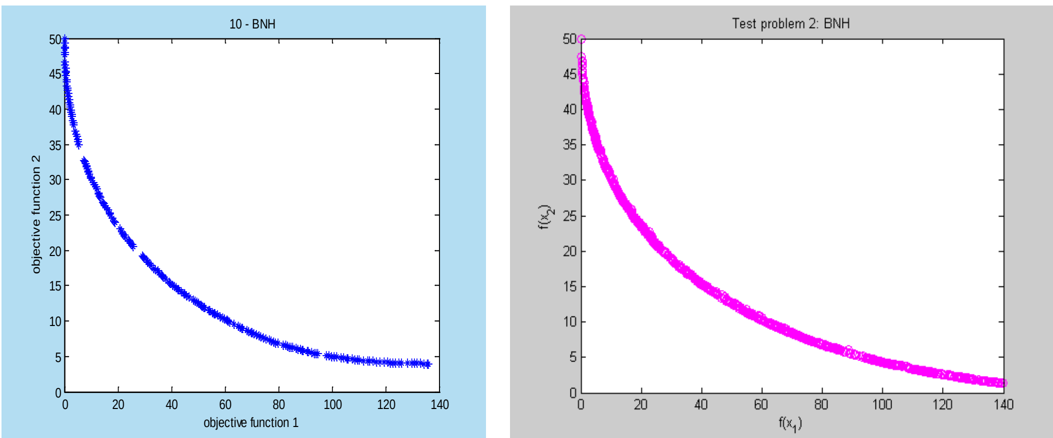
To run the MOISAT algorithm, the following default parameters are used: population size = 100; maximum number of generations = 500; crossover probability = 0.9; mutation probability = 0.05; crossover distribution index = 20; and mutation distribution index = 20.

The Pareto optimal fronts obtained by NSGA-II and MOISAT for KUR, BNH and ZDT3 test problems are depicted in Figure 8.10, Figure 8.11 and Figure 8.12. The results show that both MOISAT and NSGA-II obtained the best results for all the test problems and exhibit better performance in terms of convergence and diversity. MOISAT successfully converged to optimal solution and produces solutions having uniform distribution for the BNH test problem. For the ZDT3 test problem, the non-dominated solutions returned by MOISAT are distributed equally but not well converged with respect to the true Pareto front. The results reveal that MOISAT does not have any difficulty in achieving a good spread of Pareto-optimal solutions for both constrained and unconstrained multi-objective optimization.



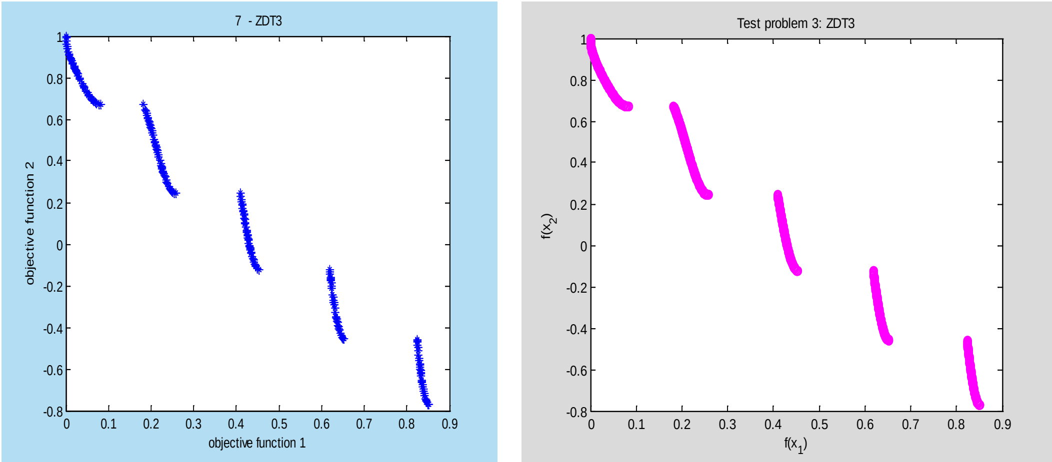
(a) NSGA-II (KUR) (b) MOISAT (KUR)

Figure 8.10 Pareto fronts for KUR benchmark test problem



(a) NSGA-II (BNH) (b) MOISAT (BNH)

Figure 8.11 Pareto fronts for BNH benchmark test problem



(a) NSGA-II (ZDT3) (b) MOISAT (ZDT3)

Figure 8.12 Pareto fronts for ZDT3 benchmark test problem

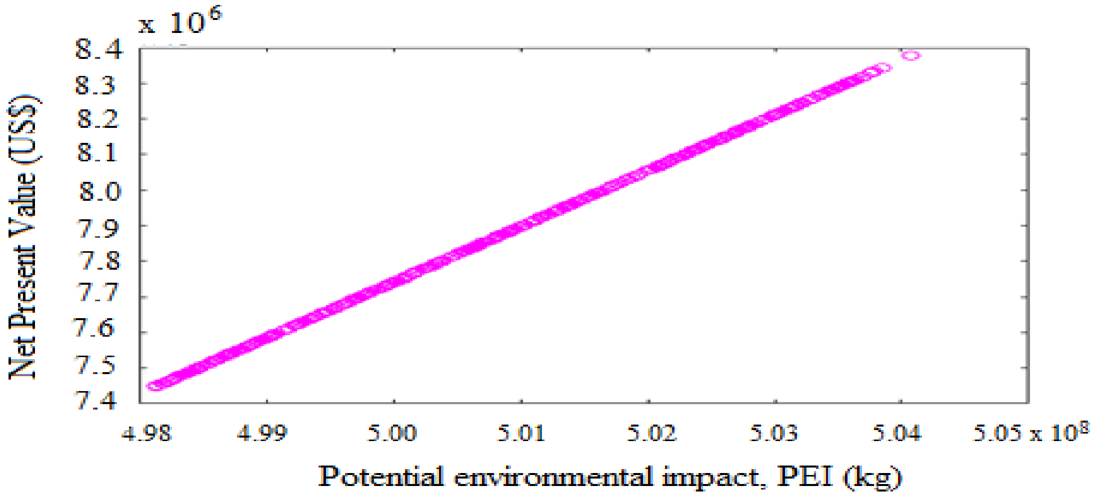
8.7.2 Model application and empirical results

In order to evaluate the performance of the model proposed in this research, the tea production system in Malawi is taken up as a case study. Data pertaining to prices, costs, and capacities has been collected from tea companies in Malawi and fed into the tri-objective model. The proposed algorithm is implemented with MATLAB programming environment and solved using NSGA-II. All the computational studies were executed on a DELL OPTIPLEX 990 desktop with Intel (R) Core (TM) i5- 2400 CPU @ 3.10 GHz processor and 4 GB RAM, using windows 7 64-bit operating system. The proposed model aims to simultaneously optimize the economic, environmental, and social performance of the multi-objective tea supply chain problem. The multiple objective functions are denoted as f_1, net present value maximization; f_2 minimization of environmental impacts; and f_3, maximization of job opportunities created; f_4 minimization of work days lost due to injuries; and f_5 minimization of total annualized costs. The decision variables are quantity of made tea produced at the factory, market price of tea, discount rate, and amount of capital investment. To apply the MOISAT algorithm for optimal and sustainable performance of the tea industry, the following default parameter is used: population size = 100; maximum number of generations = 500; crossover probability = 0.9; mutation probability = 0.05; crossover distribution index = 20; and mutation distribution index = 20.

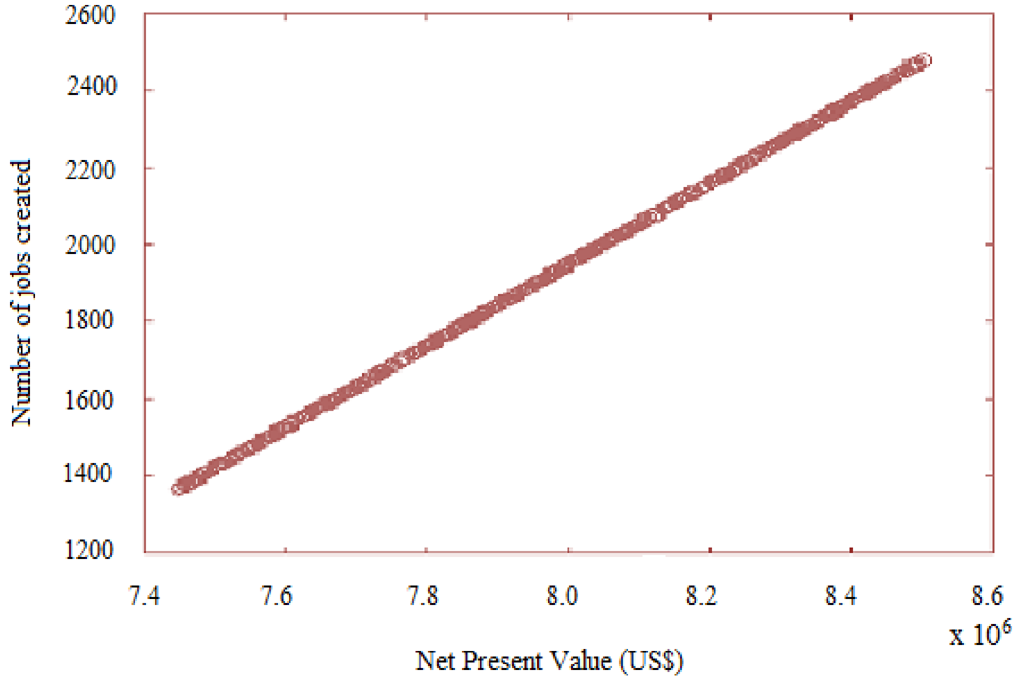
The tri-objective optimization problem maximizes the NPV and social benefits, and simultaneously minimizes the emissions. The multi-objective optimization problem is solved using the weighted sum approach. Figure 8.13 presents the trade-offs that exist among the economic, environmental and social objectives. However, creating a three-dimensional plot requires many points for vectorization. To facilitate the graphical visualization and sustainability trade-off analysis of the entire Pareto set, the researcher decided to present a number of two-dimensional Pareto optimal solutions. These two-dimensional charts represent the trade-offs between two of the three objectives which satisfy a threshold level set on the third objective. Thus, Figure 8.13 displays three different views of the same three-dimensional (3-D) scatter plot. In the first subplot, the y-axis of the Pareto curve represents the number of jobs and the x-axis represents the NPV. For the second subplot, the vertical coordinate is the NPV, whereas the horizontal coordinate is the emission in unit of ton/year. For the third plot, the y-axis represents the number of created jobs and the x-axis represents the emissions in unit ton/year. The emissions presented in the Pareto front are based on the cradle-to-gate LCA.

The analysis of the Pareto-optimal fronts exhibited trade-off between economic and environmental performance. The results given by the used case study show a positive association between the economic and environmental as well as social performance. The NPV increased linearly with the potential environmental impact (PEI) resulting from the operation of tea plant. The expected optimum NPV is $8,184,703 over a 30 year estimated plant life with an annual discount rate of 10%. The corresponding PEI is 50 283 tons.

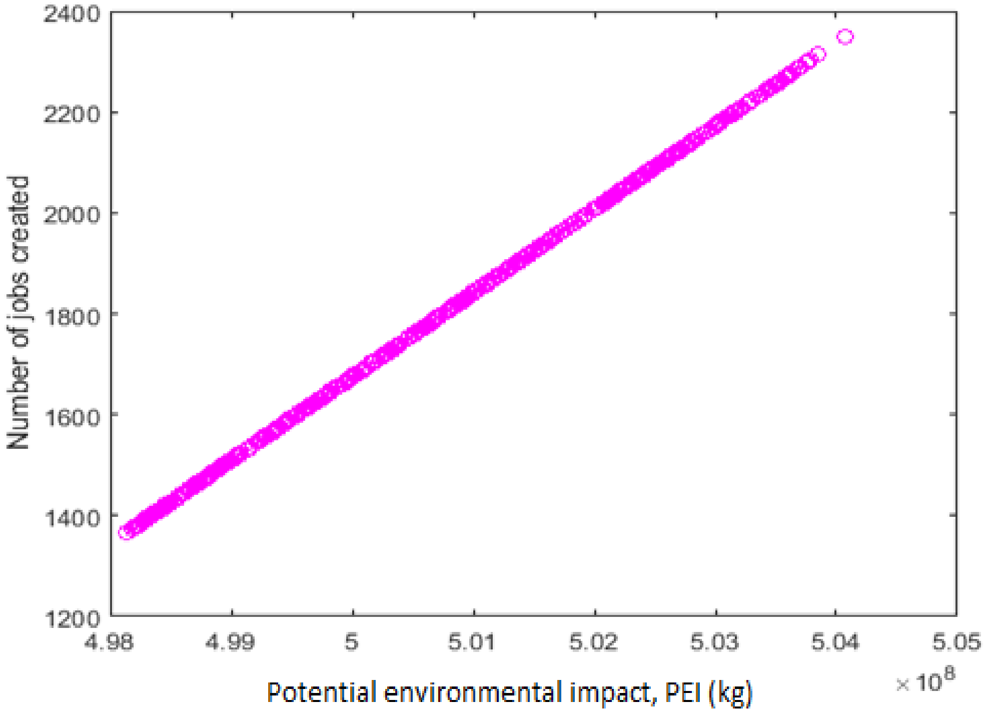
The findings of this study also indicate a positive relationship between the number of jobs created and the NPV (profitability). This result clearly demonstrates that more jobs are created when the NPV (profitability) of a company increases. For this case study, the optimum number of jobs created by the case study is 2 145, which represents an increase of 66% from the base case figure of 1 295. The number of jobs created per ton of tea is calculated as 0.92. The number of jobs created due to tea cultivation and processing depends on harvested tea area and the capacity of the plant. Results further show a positive association between the level of potential environmental impacts (PEI) and the social benefits of increased tea production. The model provides solutions which have a greater positive impact on the environment and create more jobs.



(a)



(b)



(c)

Figure 8.13 Pareto fronts for NPV, PEI, and Njobs

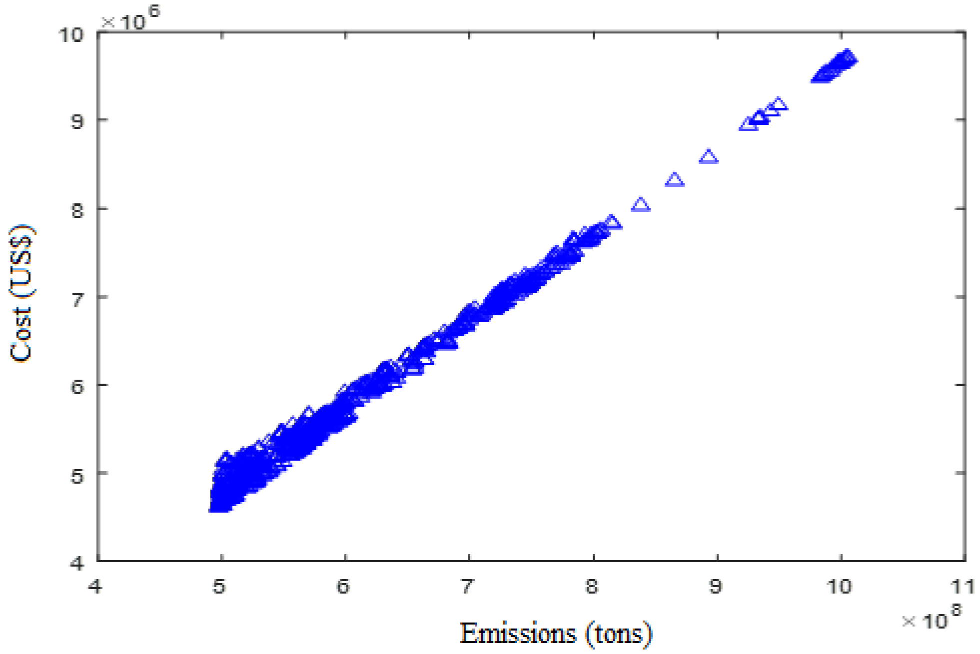


Figure 8.14 Pareto front for cost versus emissions

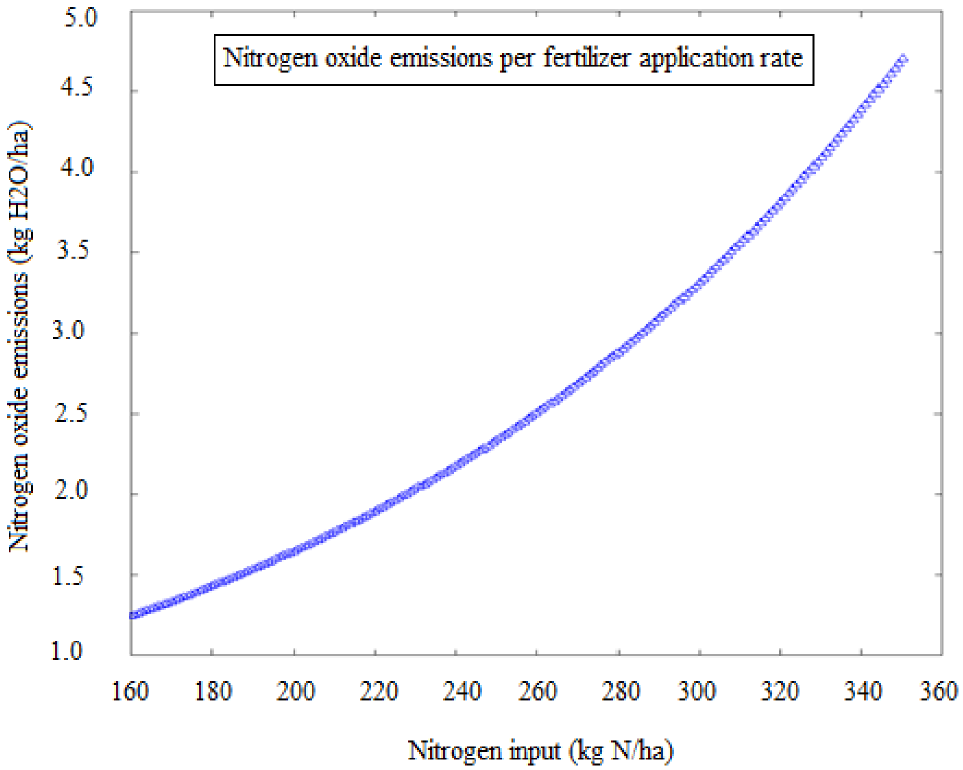
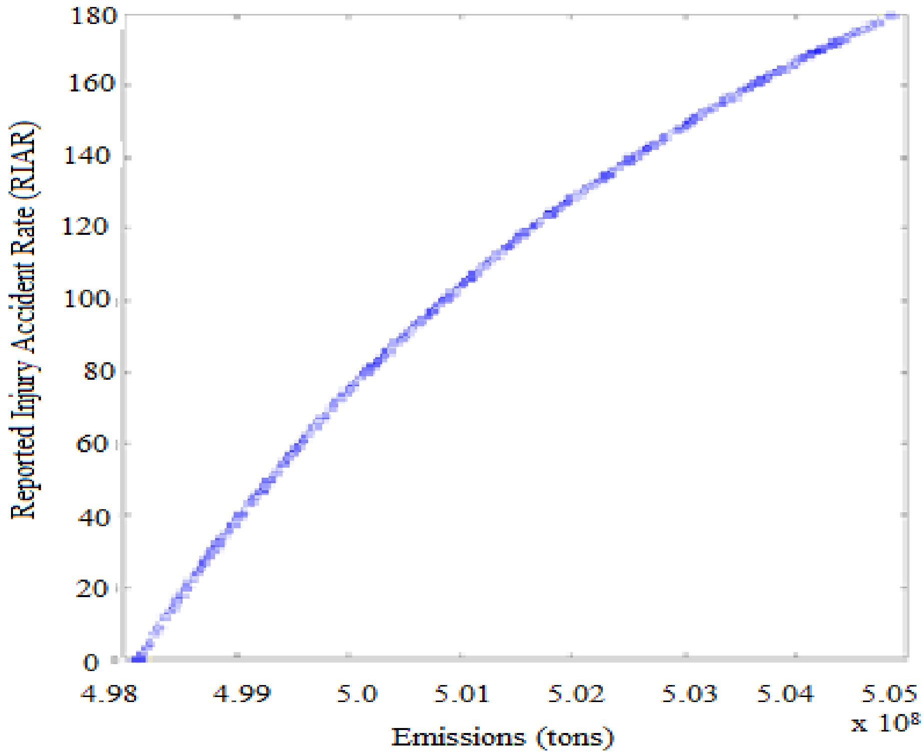
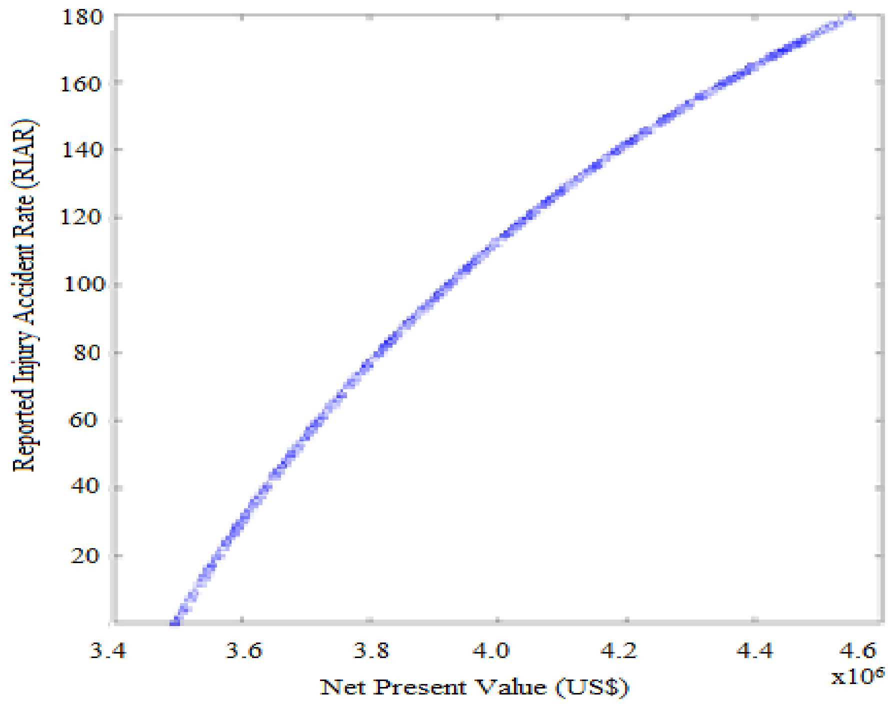


Figure 8.15 The effect of nitrogen fertilizer application on N_2O emissions

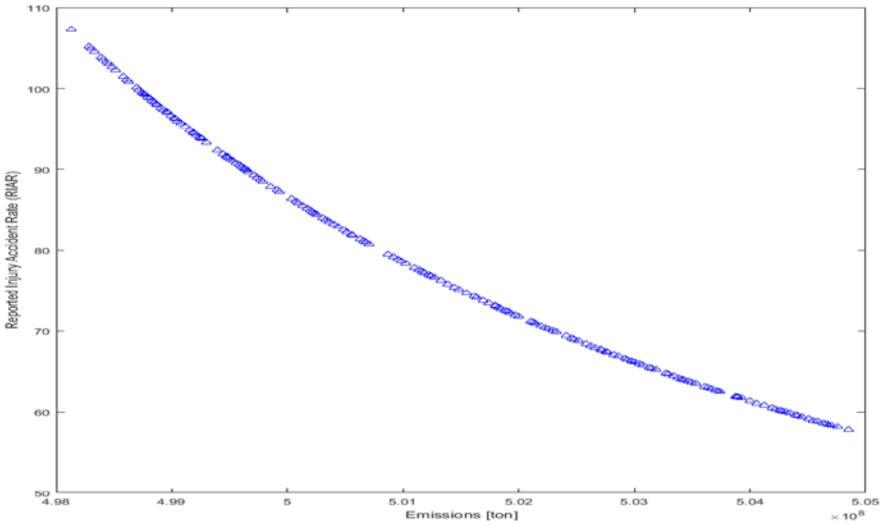


(a)



(b)

Figure 8.16 Pareto fronts for **a** RIAR versus emissions; **b** NPV and RIAR



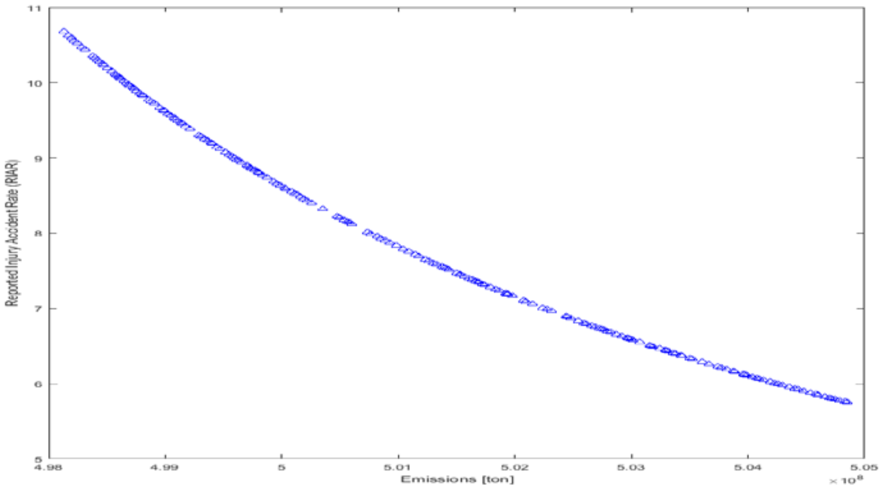


Figure 8.17 Pareto front for Scenario 3: RIAR versus PEI

Table 8.17: Relationship between costs, emissions and jobs created

Run	Costs (US$)	Emission (tons)	Jobs (nr)
1	5 345 936	56 863	1 185
2	4 868 563	50 009	2 422
3	8 901 363	92 356	1 176
4	5 445 539	51 896	4 712
5	9 676 186	99 873	1 303
6	5 267 696	53 812	2 725

Figure 8.14 shows the relationship between total costs and emissions from tea production processes. The total cost, PEI and number of created jobs are summarized in Table 8.17. Results indicate that there is no clear signal with regard to the association between pollution performance and input cost factors in tea production. However, it can be observed that annual production cost is linearly proportional with the pollutant emissions. The optimum cost of operations is US$5 267 696, and the corresponding pollutant emissions and number of jobs created is 53 812 tons and 2 725, respectively (Table 8.17). As the total costs increase, the number of jobs created decreases. Another important observation is that: as the emission level increases, the cost of production increases as well. Figure 8.15 plots the relationship between nitrous oxide (N_2O) emissions and nitrogen fertilizer rates. The results in Figure 8.15 show that nitrous emissions increased exponentially with increasing nitrogen fertilizer application rate. The optimum nitrogen fertilizer application rate is calculated to be 160 kg N ha^{-1}. To decrease costs and emission levels in the Malawian tea industry, tea companies should reduce the amount of fertilizer applied in tea farms.

Figures 8.16 to 8.18 depict the trade-offs that exists among injury and illness incident rate (IISR), NPV and PEI. Scenarios 1.2 and 3 assume the magnitude of injury and illness incident rate to be less than 10, between 10 and 100, and less than 200, respectively. The results in Figure 16 suggest that the injury severity rate is linearly proportional with the NPV and PEI. For the third scenario, the optimum NPV is calculated to be US$3 842 756 and the corresponding PEI is 500 344 tons. The injury and illness severity rate is determined to be 85.77. These results should be interpreted to mean that based on 200 lost work days for 286 863 man hours of tea operations, this company would experience 85.77 days lost by the time they reached 200 000 hrs. The findings of this study should be treated with caution, as comprehensive and exact information on the work days lost and total hours worked are not available. For the second scenario, the optimum NPV is US$3 748 169, corresponding to the PEI value of 49 9740 tons and an injury severity rate of 66.28. Results of this study clearly demonstrate the extent of safety anomalies by revealing how critical the injuries and illnesses are. The proposed model can be used to estimate the organization performance on safety.

8.8 Chapter summary

In this chapter, three case studies are used to verify the MOISAT model. The economic and financial aspects of modernizing a tea production system has been investigated using data from an existing tea factory installed in Malawi. A spreadsheet model incorporated in MOISAT was used to calculate the net present value (NPV), discounted cash flow rate of return (DCFROR), return on investment (ROI), and benefit-cost ratio (BCR). The unit production cost (US$1.33/kg) and fixed capital investment (US$2 385 739) for a modernized plant have been estimated. The total revenue was US$3/year which is realized from the sale of 2 332 737 kg of made tea at an average price of US$1.60/kg. The economic analysis revealed that a typical tea factory, with an equipment lifetime of 30 years can generate a NPV of $3 163 106 at 10% default discount rate. The return on investment (ROI) was 56%, the discounted cash flow rate of return (DCFROR) was 13.6%, and the benefit-cost ratio was 1.02. The findings indicate that investing in new technology for tea production is profitable**.**

Sensitivity analyses have been performed to evaluate the effect of economic parameters on the performance of the plant for the various specified ranges of the input variables such as capital investment, tea sales price, sales volume, discount rate, operating income, corporate tax, and revenue. Results of the sensitivity analyses show that the NPV has the highest sensitivity to changes in the selling price of tea. The simulations show that as the selling price increases, the NPV increases. The analysis further showed that at the baseline tea price of US$1.60/kg, the plant is economically viable while a price below US$1.50/kg should be avoided as the operation cannot be profitable. Discount rate was also found to be one of the factors affecting the NPV while the system was tested between 5-15% changes in discount rate.

The economic analysis also showed that the operating income of the base case study is particularly sensitive to changes in the amount of made tea sold. The volume of tea production has a large effect on the operating income and revenue, which increases with the increase in the amount of tea sold. The project would not be profitable for sales volume decrease of 10% or more. Thus, an investment like this is subject to some risk related to market conditions.

The environmental performance analysis presented in this chapter has identified the environmental hot spots of the life cycle of the Malawian tea industry. The environmental profile of the base case study organizations was strongly dominated by the manufacture and fertilization phases. The life cycle inventory results indicated that the manufacture stage is the step with the highest consumption of energy and offers the greatest opportunities for improvements in environmental performance. The manufacture stage was found to be the main contributor to most environmental categories. The impact of the manufacturing stage predominantly came from the consumption of energy sources. The fertilization stage has the second highest contribution to most environmental categories. The emission of nitrate due to the high use of mineral fertilizers contributes significantly to some impact categories, notably eutrophication and acidification. Other stages such as cultivation, irrigation, spraying, plucking (harvesting), and crop transportation, contributed little to the environmental impact categories compared to the manufacture stage.

The LCA results clearly indicate that most environmental problems deriving from the agricultural phase of tea production can be attributed to the chemicals used for soil nutrient management. The study found that the intensive use of fertilizers and soil amendments such as lime and dolomite, is the main contributor to the environmental impact of tea production. Further optimization efforts to reduce the environmental impacts of the industry could focus on better management of nutrients and reduction of the use of excessive fertilizers. Additionally, the most serious problem arising from the industrial phase is the emission of greenhouse gases arising from biomass and diesel combustion. Strategies to improve performance could include implementation of energy efficiency programmes as well as optimization of tea processes.

This chapter has presented the social life cycle assessment model for the tea industry. The model was implemented with three case studies on tea production processes in the Malawian tea industry. The overall results showed that the case study companies have poor social performance, with social hot spots found in every stage of the product life cycle. The results reveal that in this industry, human rights, particularly, forced labour, sexual and gender discrimination are the main issues. Poor working conditions, specifically, long working time, low wage/salary, and labour casualization were identified as being the most noticeable social hot spots that have to be addressed. The results obtained indicated that workers were most affected in investigated subcategories, while local community and society were to some extent positively affected within the life cycle of tea. Tea companies therefore need to make significant improvement on a number of social aspects of its operations with regard to workers. The model and its demonstration with the case studies have shown appropriate criteria that should be used to assess the social sustainability of tea production processes. The model also helped to pinpoint social sustainability hot spots within the tea production life cycle stages that need further improvement. More importantly, findings of this study confirmed s-LCA as a potential suitable tool for social assessment of company's products, processes and activities in the tea industry.

This chapter has also presented optimizations results of the developed model. The optimization model is designed as a multi-objective optimization problem taking into account three conflicting objectives. The model has been implemented in a MATLAB programming environment and solved using the NSGA-II algorithm. The algorithm provides the Pareto fronts, which are efficient solutions so that decision makers can use it in production operations. The Pareto solutions are determined via the weighted sum method. This work demonstrates that evolutionary algorithms provide a successful way of dealing with multi-objective optimization problems. There are certain deficiencies in the model, mainly from input data and some improvement work is ongoing.

Chapter-9
Conclusions and Future research

9.1 Introduction

The overall purpose of this study was to develop an integrated multi-objective optimization tool to support decision-making processes in the Malawian tea industry. This work, in particular, aimed to create a tool for measurement, evaluation and subsequent improvement of sustainable performance in this industry. The primary question of the study was: "How can decision makers in the tea industry be empowered to achieve sound financial performance within environmentally sustainable and socially responsive bounds?" To address this research question and to achieve the purpose of this study, the research problem was broken down into five objectives:(i) to empirically investigate the current sustainability practices in the Malawian tea industry; (ii) to identify and understand critical factors that influence productivity and sustainability of tea processing companies; (iii) to explore and describe the existing literature on theory and practical interventions (globally) in pursuit of environmental, social, and economic performance related to tea production; (iv) to develop an integrated optimization model that maximizes the economic and social value of the tea production system in Malawi, while minimizing its most significant environmental impacts; and (v) to evaluate the performance, usability and reliability of the created tool by case studies.

Chapter 1 presented the background of the study and significance of the work reported in this dissertation. The chapter also introduced the research problem and the research objectives. The background regarding the situation of the Malawian tea industry, major challenges facing it and its environmental as well as social impacts were provided in Chapter 2. This was followed by a literature review on the current state of knowledge in sustainable production and productivity presented in Chapter 3. Chapter 4 provided a comprehensive review of multi-objective optimization. It summarized the basic principles of multi-objective optimization and introduced the concepts of dominance and Pareto optimality. Chapter 5 described the research methodology, philosophical assumptions underpinning the study, research design and strategy as well as the method of data collection and analysis. Chapter 6 presented results of the data analysis and findings of the industrial survey. Chapter 7 proposed the development of the decision-support tool for optimally operating production processes while minimizing cost and environmental impacts and maximizing the long-term sustainability. Chapter 8 reported on the model's verification, validation and demonstration.

This concluding chapter summarizes the whole dissertation, discusses its salient findings and contributions, highlights the limitations of the study, and provides directions for future research. The chapter is divided into six main sections including this introduction. The first section, 9.1, introduces the chapter. Section 9.2 describes the key findings of this research, specifically focusing on the six research questions presented in Section 1.6. First, it addresses the Research Question 1, determining the current levels of sustainability (or the lack thereof) in the Malawian industry. The section also focuses on Research Question 2, identifying critical factors influencing the productivity of tea manufacturing companies. It then examines the environmental, social and economic factors of tea production, focusing on Research Question 4. Finally, it addresses Research Questions 5 and 6 by developing and empirically testing the created tool in three purposively-selected tea companies. Section 9.3 presents a discussion of the research contributions. The next section, 9.4, highlights the limitations of the current research. Section 9.5 discusses the future research directions, and finally Section 9.6 concludes the thesis.

9.2 Summary of research findings

The findings of the research are based on the objectives of the study and are discussed below:

9.2.1 Awareness and knowledge of sustainability practices

This study began with the examination of the status of sustainability production practices in the tea industry. It aimed at assessing attitudes and perceptions of tea decision makers and other stakeholders towards sustainable production. Furthermore, the study sought to investigate the awareness and understanding of managers and stakeholders about sustainable business practices; the importance given to sustainability; drivers that stimulate the implementation of sustainability practices; and potential barriers with their implementation. Data collection was primarily conducted by industrial surveys, semi-structured interviews, observations, and document analysis. Structured as well as semi-structured interviews were conducted with representatives of eight tea companies, purposively, selected from the list of all tea companies operating in the country. The results of this exploratory and descriptive study were presented in sub-chapter 6.4.3.

The results showed a fairly high level of awareness towards sustainable business practices and that these were of increasing importance to the Malawian tea industry. However, the awareness of sustainability issues has not yet been translated into practice. The results of this study indicated overall positive attitudes and perceptions towards sustainable business practices. The study found that tea firms adopt sustainability production practices because it offers significant reduction in costs, resulting from improvements in the product, process quality as well as improvements in efficiency and productivity. This result suggested that cost savings is a strong driver to a broader shift to sustainable production. This finding is consistent with other research conducted around the world where cost saving is considered being a strong driver influencing adoption of sustainability practices (Barney, 1991; Siegel, 2009). The results are echoed in Nidumolu *et al*., (2009), that claim that sustainability practices offer companies opportunities to save costs.

Furthermore, the analysis of the results portrays that the main barrier to implementation of sustainable business practices was the lack of practical tools for measurement and evaluation of sustainability performance in the tea industry. The study revealed that a limited number of sustainability initiatives has been implemented over the past few years due to a lack of appropriate strategies. The key conclusion is that sustainability production practices are not currently evident within the Malawian tea industry and that companies need assistance in realizing and managing sustainable production.

The researcher also developed a model to capture sustainability performance sub-indices in economic, social, and environmental categories, and provided a composite sustainability index for the industry. The output results from the model gave the total sustainability impact caused by tea production processes a score of 0 to 1. The results indicated that the Malawian tea industry is at medium level of sustainability, with an index value of 0.4995 and requires more improvement especially in the environmental and social dimensions of sustainability.

9.2.2 Factors influencing sustainable productivity

The aim of this section of the study was to investigate critical factors that influence the productivity of tea processing companies. This objective was achieved from the results obtained through industrial surveys. A survey research method, combined with face-to-face interviews was used to collect the data. The respondents rated the importance of productivity factors with a 5 point rating scale ranging from 1 (strongly disagree) to 5 (strongly agree). The findings of the study enabled the researcher to identify and classify factors affecting productivity of the tea industry in seven groups: human capital, machine capital, material, method, control, process, and product factors. The study highlighted the material group as being the most critical factor affecting productivity. This was not surprising, as materials are essential for tea production and processing. The lack or shortage of materials negatively affects the productivity of the industry since this results in factories being forced to shut down for a considerable number of months or run at reduced capacity. The findings of the study indicated that it is important to focus on critical factors that may affect productivity of manufacturing.

The study also found that the quality of materials, green leaf in particular, alongside maintenance affects the yield of main grades of tea, which in turn, fetches lower or higher prices at the auction markets, thereby affecting both the profitability and productivity of the tea industry. Therefore, decision makers in this industry should pay proper attention to machine utilization, age, modernization, cost, and investment. The key conclusion from these results was that material factors have a strong effect on the productivity and subsequently, the sustainability of the tea industry.

9.2.3 Environmental, economic and social impacts of tea production

The third objective of this study was to investigate the environmental, economic and social impacts related to tea production. This objective was achieved from the results obtained through the industrial survey as well as extant literature reviews. The results of this industrial survey were presented in **sub-chapters 2.4** and **2.7**. The results from field research showed that tea production makes significant contributions to economic growth, value addition, and employment and wealth creation. Tea production, however, causes serious environmental damage due to its use of agrochemicals. Extensive use of agrochemicals (fertilizers and pesticides) pollutes the soil and decreases water quality.

In addition, harvesting of firewood for tea drying causes deforestation, contributing to a loss of biodiversity, both in terms of plant and animal species, as well as soil degradation. The negative social impacts associated with tea production are identifiable in human rights and working conditions. The study specifically found that the tea industry is plagued with sustainability issues such as poor and dangerous working conditions (low wages, low income security), child labour, and gender discrimination. This result corroborates the finding of Wal (2008), with the study focusing on a comparative analysis on social, economic and ecological conditions in the tea sector in India, Sri Lanka, Vietnam, Indonesia, Kenya and Malawi. The study further revealed that the environmental impacts of tea production were considerable: notably reduced biodiversity, high-energy consumption, and high application of pesticides. This result strongly suggests that the Malawian tea industry is not sustainable, and therefore, needs to improve in these hot spot areas.

9.2.4 Develop an optimization model for the tea industry

The next objective of this study was to develop an integrated optimization model that maximizes the economic and social value of the tea production, while minimizing its most significant impacts. The researcher developed a mathematical model to maximize the net present value and social benefits while minimizing the environmental impacts of the tea production system. The mathematical model was designed as a multi-objective optimization problem taking into account three conflicting objectives. The model was implemented in a MATLAB programming environment and solved using the NSGA-II algorithm. The proposed model combined life cycle assessment (LCA), multi-criteria decision analysis (MCDA), and multi-objective optimization methods, particularly the non-dominated sorting genetic algorithms (NSGA-II). The mathematical formulation for the model was presented in subchapter 7.4. The performance of MOISAT-NSGAII algorithm was first tested on standard benchmark problems taken from the literature.

Results showed the MOISAT algorithm yields efficient solutions in terms of giving a wide spread of solutions with good convergence to true Pareto optimal solutions.

The model was applied to a case study of a multi-objective tea production system problem, which identifies a set of alternatives that define optimal solutions to the problem. The results obtained showed that the developed model was effective and had great potential for solving multi-objective optimization problems in the tea industry. The model also provided a basis for different stakeholders in the tea industry to easily see the trade-offs between different sustainability aspects, allowing them to make informed decisions.

9.2.5 Empirical testing

The purpose of this section of the study was to test the validity of the developed tool empirically. The developed model was applied to a real case study to select the best solutions to multi-objective optimization problems of the tea industry. System integrated testing was conducted with the aim of verifying that all related systems in MOISAT maintain data integrity and can operate in the tea industry. In addition, usability testing was also performed to gauge users' experience with the developed system and thereby, find any problems that prevent users from completing their tasks, slow them down, or otherwise degrade their user experience. The results of the model testing, verification and validation were presented in **subchapters 8.5.1, 8.6 to 8.9**.

The obtained results clearly indicated that investing in modern tea processing technology was profitable. Results of the sensitivity analyses showed that the NPV had the highest sensitivity to changes in the selling price of tea. The analysis found that at a baseline tea-selling price of US$1.60/kg, the plant is economically viable, while a price below US$1.50/kg should be avoided as the operation would not be profitable. The findings of this study revealed that the environmental profile of the base case study companies was strongly dominated by the manufacture and fertilization stages of tea production. The study established that manufacture stage is the step with the highest consumption of energy, which offers greatest opportunities for improvements in environmental performance.

The study also indicated that the intensive use of mineral fertilizers and soil amendments contributes significantly to some environmental categories, notably eutrophication and acidification. Further optimization efforts to reduce the environmental impacts of the industry should focus on better management of nutrients and reduction of the excessive use of fertilizers. The result showed that the most serious problem arising from the processing phase was the emission of greenhouse gases due to biomass and fossil fuel combustion.

The empirical results of this study showed that the case study companies have poor social performance, with social hot spots found in every stage of the tea production cycle. The study identified poor working conditions, especially long working time, low wages and salaries, and labour casualization as being the most noticeable social hot spots (issues) that have to be addressed. The findings of this study confirmed social life cycle assessment as a potential suitable tool for social assessment of the tea industry's processes and activities. Overall, the findings of this study could provide useful insights for industry practitioners to help them know what costs and activities along the supply chain they should focus on to maximize the social economic benefits while minimizing the environmental impacts of tea production. Thus, from the case study it can be concluded that the developed tool allows improvements in all the three dimensions of sustainability and offers important managerial insights.

9.3 Research contributions

This research has contributed to filling knowledge gaps in the extant literature as well as improving practice in the tea industry. The main contributions of this thesis can be summarized as follows:

9.3.1 Theoretical contributions

The major obstacle impeding operationalization of sustainability in the tea industry is the lack of suitable tools. The main theoretical contribution of this research is the development of the MOISAT tool, which can be used to facilitate the implementation, management and integration of sustainability issues in the tea industry. The tool can be used to analyse the sustainable performance, including environmental, economic and social impacts in each stage of the tea production life cycle. To the best of the researcher's knowledge, there is no such tool available in the literature that incorporates all three dimensions of sustainable performance in a single overarching framework for the tea industry.

The second contribution of this study is the systematic framework that enables consideration of the three-dimensional sustainability, simultaneously optimizing the economic, social and environmental impacts as well as the integration of economic, social and environmental concerns that follow life cycle analysis procedure in a multi-objective framework. The third original contribution made in the thesis is a unique NSGA-based algorithm that integrates economic indices, life cycle assessment (LCA) framework, multi-criteria decision analysis (MCDA), specifically the analytic hierarchy process (AHP), and an evolutionary multi-objective optimization algorithm (EMOA).

Another significant contribution from this research is new knowledge and understanding of sustainable production and sustainable development. This research reports the current situation concerning sustainable production and challenges confronting its realization in the Malawian tea industry. The overview of the current situation and challenges is undoubtedly beneficial for both industry and academia as it enables identifying actions required for improving sustainability performance. Hence, it provides the basis and support for realizing sustainability in the tea industry.

The fifth contribution of this work is the development of sustainability indicators for the tea industry. The need for developing tea industry-specific indicators was identified during the industrial survey. The study has proposed various sustainability indicators and metrics that can be used to support decision makers in setting goals, gauging a company's progress, benchmarking, and comparing business and technology alternatives in terms of sustainability. In addition, the sustainability indicators in MOISAT are evaluated in different ways. Economic and environmental indicators are quantified in different units, whilst the social indicators are qualified in a value. The research offers a way to combine the qualitative and quantitative data in the assessment of sustainable performance.

9.3.2 Practical-applicative contributions

The most important contribution from this research to practice is the integration of three life cycle models that assist decision makers in the tea industry to understand the sustainability performance of their products, processes, and activities. These models can be used to analyse the different impact categories of environmental, economic and social aspects. The models can also be applied integrally or individually for decision-making. The model also provides a basis for different stakeholders in the tea industry to see the trade-offs between different sustainability aspects easily, allowing them to make informed decisions. The tool can also facilitate decision-making by helping decision makers to better understand the decision and the consequences of their decision for sustainable production.

This study provides insight for managers and decision makers in the tea industry regarding the challenges that exist in the industry and how they affect long-term sustainability of their business and operations. These findings will further shed light on forming corporate strategies to overcome challenges and to achieve a competitive advantage while increasing long-term sustainability.

9.4 Limitations of the study

Several limitations to this study influence its validity and authenticity. Some of these limitations relate to the sample size, research methodology, data collection, and time constraints. These limitations, which give rise to further research, are discussed below:

9.4.1 Limitations relating to sample selection

The study was limited by the relatively small convenience sample eight out of twenty-one in Malawi. A random sample from the pool of tea companies would have increased the generalizability of the results. In addition, due to time and financial constraints, the developed tool was tested and validated in three case study companies, which represent only 14% of the population. This may affect the generalizability of the results derived from this study. The result of the study would have been different if more factories and more representative sample were included in the testing and validation of the developed tool. Therefore, there is a need to increase the coverage of similar empirical studies to obtain a more comprehensive picture on the applicability of the developed tool.

9.4.2 Limitations due to non-disclosure of information

The second limitation of this study relates to the non-disclosure of confidential and sensitive information. The tea companies that participated in this study were only willing to share limited data in order to ward off competition. Therefore, a lot of persuasion was required to convince the concerned companies of the usefulness of the research. With the assurance of the researcher's commitment to maintain anonymity and confidentiality, the tea companies did provide the information.

9.4.3 Potential for bias

The third limitation is associated with selection bias. The findings described in this dissertation might be limited by potential selection bias. Tea companies were selected on a voluntary basis and their willingness to participate in this study. No information is presented concerning those companies that declined to take part in this research, which could limit the generalizability of these findings.

9.4.4 Limitation due to data collection

Methodological limitations also arose from the focus of the study. The main one is that the validity of the results depends on the sincere reporting of the key informants interviewed and their ability to recall past events accurately and precisely. The subjectivity inherent in the scoring process or weighting of sustainability indicators is also another limitation. Furthermore, empirical testing of the developed tool covered a short period of time [one tea growing season], which may raise further uncertainty about the generalization of the results. In order to improve the reliability of the research results and to increase the generalizability of the research findings, there is a need for an extension of the analysis to include more factories, as well as a longer period of time, which may help to validate this study.

9.4.5 External validity

The results of this study might be limited by the issue of the external validity and the extent to which the findings of the research study are relevant to tea industries and settings beyond those in the present study. The conclusions derived from this study are based on analysis of eight tea companies. The results can be generalized for all tea companies in Malawi that could be used as a basis to make informed decisions. However, the results may differ for tea companies located in different countries that are operating under different cultural, environmental and political conditions. Therefore, findings of this research require further studies in order to be generalized with tea industries that have similar settings with the Malawian tea industry.

9.4.6 Model-specific limitations

A key limitation of this study concerns the use of commercial software. The use of commercial software, MATLAB as an optimizer is also one major limitation for wider application of the developed tool. This could be addressed by implementing the NSGA-II algorithm in alternative open source software such as OCTAVE and Visual Basic. Despite these limitations, this study provides valuable insights from theoretical and practical perspectives. The results contribute to a better understanding of the factors that determine sustainable performance of the tea industry. Furthermore, the results have strong implications regarding the implementation of sustainable strategies. The study authenticates the developed tool as being suitable to support decision-making processes in the tea industry.

9.5 Future research directions

The work presented in this thesis has developed a tool that can be used to support decision-making on the sustainability of the Malawian tea industry. There is no question that the three topics investigated in this work are extremely diverse and complex. Admittedly, this research has just barely scratched the surface compared to the magnitude of issues under the umbrella of sustainable production. Within the broader context of sustainable production, there are arguably multitudes of issues yet to be resolved and urgently requiring further research. The findings of this research study provide insights for future research. The recommendations for further research are as follows:

- **Extend MOISAT validation in other tea producing countries**
  This study is situated in the context of the tea industry in Malawi. The design offers several advantages such as controls for industry and geographic effects. However, the design may limit the generalizability to other countries operating under different settings. Future research should consider validating the developed tool in different country contexts.

- **Expand system boundary to cover the whole life-cycle of tea**
  This research conducted both environmental and social life cycle assessments by considering a cradle-to-gate system boundary. Upstream activities such as the manufacture and transportation of farm inputs, nursery establishment, forest management as well as distribution and usage were, however, excluded from the analysis. Future research should expand the system boundary to cover the whole life-cycle of tea.

- **Develop a local life cycle inventory database and life cycle impact assessment method**
  To reduce the model uncertainty, further studies on national and or local parameters used in the model, such as emission factors, classification factors, normalization factors, and weighting factors are needed. Emission,

classification and normalized factors used in this study are based on international sources. There is a need to develop a local life cycle inventory database as well as a life cycle impact assessment method for Malawi.

- **Link performance indicators and measurement to an improvement and management system**
  The developed tool aims to assist decision makers in the tea industry to measure, improve, and manage sustainability performance. However, further research work on the MOISAT model is required, particularly to link performance indicators and measurement to an improvement and management system.

- **Develop mobile and website data collection system**
  Finally, a key limitation of the developed tool is its data intensiveness of the life cycle information. Further research should incorporate mobile as well as website data collection. To this end, the existing software will need to be programmed in Visual Basic, with SQL Server Data Management System for data entry.

9.6 Concluding remarks

This chapter has summarized the research work conducted in this doctoral study. The chapter began with a review of the first eight chapters presented in this dissertation. Focus then turned to the key research findings, followed by an account of limitations of the study and then an assessment of its contributions at the theoretical and application levels. This naturally led to discussion of implications and then recommendations, which included those relating to further research. The central contribution of this study is the development of an integrated multi-objective optimization tool to support decision-making processes in the tea industry. Furthermore, the research contributes to filling the existing gaps in research in the Malawian tea industry. In this way, this chapter ends this dissertation.

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