COLLABORATIVE INNOVATION, LIFE CYCLE ANALYSIS AND NETWORK OPTIMISATION – ESSAYS ON FOOD SUPPLY CHAIN SUSTAINABILITY

A THESIS

Submitted by

Ramesh K

for the award of the degree

of

DOCTOR OF PHILOSOPHY

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Indian Institute of Technology Madras

Business School

University of Technology Sydney

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CERTIFICATE OF ORIGINAL AUTHORSHIP

I, **Ramesh K**, declare that this thesis, is submitted in fulfilment of the requirements for the award of **Doctor of Philosophy**, in the Business School at the University of Technology Sydney.

This thesis is wholly my own work unless otherwise referenced or acknowledged. In addition, I certify that all information sources and literature used are indicated in the thesis.

I certify that the work in this thesis has not previously been submitted for a degree nor has it been submitted as part of the requirements for a degree except as fully acknowledged within the text.

This thesis is the result of a research candidature jointly delivered with **Indian Institute of Technology, Madras** as part of a Collaborative Doctoral Research Degree.

The research presented and reported in this thesis was conducted in accordance with the National Statement on Ethical Conduct in Human Research 2007. The proposed research study received human research ethics approval from the University of Technology Sydney Human Research Ethics Committee, Approval Number - ETH8-2983. This research is supported by the Australian Government Research Training Program.

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QUOTATIONS

The deeper a well is dug, the more the water that springs;
the more one learns, the more the wisdom it brings (396).

\- *THIRUVALLUVAR*

DEDICATION

I wish to dedicate to

My Parents,

My Supervisors,

My Friends,

My Wife,

My Son,

Agaram Foundation,

&

My Well Wishers

All these people made me what I am today.

THESIS CERTIFICATE

This is to certify that the thesis titled **LIFE CYCLE ANALYSIS AND NETWORK OPTIMISATION –ESSAYS ON FOOD SUPPLY CHAIN SUSTAINABILITY**, submitted by **RAMESH K**, to the Indian Institute of Technology Madras, Chennai and University of Technology Sydney, Australia, for the award of the degree of Doctor of Philosophy, is a bonafide record of the research work done by him (her) under my (our) supervision. The contents of this thesis (or project report), in full or in parts, have not been submitted to any other Institute or University for the award of any degree or diploma.

Place: Chennai
Date: 14th Dec 2020

Production Note:
Signature removed
prior to publication.

Dr Arshinder Kaur
Research Supervisor
Professor
Dept. of Mgmt. Studies, IIT Madras
Chennai 600036, India.

Production Note:
Signature removed
prior to publication.

Dr Renu Agarwal
Research Co-Supervisor
Associate Professor
UTS Business School
NSW 2007, Australia

Production Note:
Signature removed
prior to publication.

Dr Christopher Bajada
Research Co-Supervisor
Associate Professor
UTS Business School
NSW 2007, Australia

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ABSTRACT

KEYWORDS: Food Supply Chain; Operations Research; Sustainability; Network Design; Food Waste Valorisation; Life Cycle Assessment; Farmer Producer Organisation; Multi-objective Optimisation; India.

The food supply chain is characterised by long lead times for the production of agricultural products, seasonality in production and consumption of food products, variation in quality and yield of products, special requirements for handling food products such as cold storage and perishable nature of food products – all of which make the management of the food supply chains complex and difficult. The presence of isolated and independent operations across the food supply chain also hampers collaborative efforts and leads to economic inefficiencies and environmental degradation. This is further compounded by food waste across the stages of the food supply chain – from the early stages of harvesting to processing, packaging, handling, storage, distribution and consumption. According to the Food and Agriculture Organisation, approximately one third of the global food production is wasted or lost annually. Collectively these issues necessitate research on this area as a means for developing effective solutions that ensure the effective management of food supply chain operations to meet the growing demand for food.

Further, in this contemporary business world, competition from globalisation, increased food mile due to globalisation and trade, a heightened awareness by the consumer for high quality products and transparency in operations, rising population and their food demand and strict government regulations places greater pressures on the limited resources needed to make goods and services. A culmination of such factors now mean that sustainable practices are becoming a necessity rather than a preference. Further, the increasing demand for food products to meet the growing population puts

pressure on natural resources and necessitates the sustainable way of producing and consumption of natural resources as well as reducing the food wastages at all stages of the food supply chain. Accordingly, there is a need for research that identifies opportunities for improving the sustainability of the food supply chain.

Based on the review of existing literature, this study has identified and addressed several research gaps. First, firms today are striving to adopt innovations to ensure their survival, value creation and success. Innovation is increasingly seen as an outcome of a collaborative process, involving various stakeholders both within and outside the firms, in supply chain relationships. This leads to the notion of supply chain innovation, which has been widely accepted as an important ingredient for improving the organisational and supply chain performance of firms. Inefficient practices such as improper crop selection, the involvement of too many intermediaries, flood irrigation, over-fertilization and food waste necessitate innovative practices that will improve the sustainability of the food supply chain. In this regard, there is a lack of studies that investigates how collaboration among food supply chain entities leads to innovative practices and how these innovative practices, in turn, improve the sustainability of the food supply chain. Based on the case study approach, using the case of the Indian farmer producer organisations, this study has identified several innovative practices and the sustainable outcomes.

Second, whilst India is the major producer and exporter of many crops, there is a lack of research that evaluates the environmental impact of the Indian FSCs. The environmental impact of the same product varies according to the resources consumed and so it is important that the environmental impact of individual supply chains be considered. There is a lack of studies that use the result of the environmental impact assessment to identify the operational and resource inefficiencies in FSC and address it. In this study, based on the life cycle assessment approach as per the guidelines provided by ISO 14040 and 14044, the environmental impact of resources consumed for producing 215kg of mango pulp across the various stages food supply chain is calculated. The operational and resource inefficiencies causing these inefficiencies are identified from the result of life cycle assessment and a framework is proposed considering resource recovery and operational efficiency improvement practices for redesigning of mango food supply chain that improves environmental sustainability.

Third, food supply chain network design – a strategic decision has a significant impact on sustainability due to the involvement of a large amount of resources. Despite the significance of implementing sustainability practices, existing studies have majorly considered economic dimension alone or economic and environmental dimensions alone, leaving the impact of food supply chain operations on society. Food waste across the stages of the food supply chain has a significant negative impact on sustainability. There is a lack of studies considering food waste recovery plant as one of the entities of the food supply chain and model it despite the opportunity available for food waste valorisation. Accordingly, this study has proposed a multi objective mixed integer linear programming model for designing a sustainable food supply chain network considering the three dimensions of sustainability, shelf life and food waste recovery plant. The proposed model is applied to a real case of processed mango fruit supply chain in India. The case study elucidates trade-offs and the impact of focusing only on a particular dimension of sustainability. The impact of considering shelf life on all three dimensions of sustainability, inventory and waste generated are analysed and presented.

This study advances the existing literature on the sustainable food supply chain, provides several managerial implications to the practitioners and policy recommendations to the government and policymakers. The limitations of this present study and possible future research directions are provided.

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GLOSSARY

Food Supply Chain Management Management of series of activities from receiving farm inputs from suppliers, cultivation, processing, packaging and distribution of food products to the customers in fresh quality.

Sustainability The design of human and industrial systems to ensure that humankind's use of natural resources and cycles do not lead to diminished quality of life due either to losses in future economic opportunities or to adverse impacts on social conditions and the environment.

Life Cycle Assessment Aims to calculate the environmental impacts of resources consumed and waste generated across the stages of the food supply chain.

FPO Farmer Producer Organisations (FPO) are formed by the group of small farm landholders with the initial capital generated from the members of the FPO.

Food Waste Wholesome edible material intended for human consumption, arising at any point in the FSC that is instead discarded, lost or degraded.

Food Supply Chain Network Design Aims to find the best configuration of supply chain operational elements by determining sourcing strategies such as supplier selection, selection of location, capacity and number of facilities to open and operate and distribution strategies to meet the demand.

Supply Chain Innovation An integrated change from incremental to radical changes in product, process, marketing, technology, resource and/or organisation, which are associated with all related parties, covering all related functions in supply chain and creating value for all its stakeholders.

Supply Chain Collaboration A close and long-term relationship in which supply chain partners work together to share resources, information, and risk using different coordination mechanisms as well as solve problems and make decisions jointly to achieve mutual objectives.

Food Waste Valorisation Conversion of food waste into higher value product which can be used back in the same or different supply chain as an input/ingredient for producing a new product.

ABBREVIATIONS

AC	Acidification
CE	Circular Economy
DCT	Dynamic Capability Theory
EU	Eutrophication
FAO	Food and Agriculture Organisation
FSC	Food Supply Chain
FPO	Farmer Producer Organisation
FWAE	Fresh Water Aquatic Ecotoxicity
GHG	Green House Gas
GWP	Global Warming Potential
HT	Human Toxicity
IPP(S,M,D & R)	Innovative Practices at Plan (Source, Make, Deliver & Return) level
LCA	Life Cycle Assessment / Analysis
LRAC	Long-run Average Cost
MAE	Marine Aquatic Ecotoxicity
MOMILP	Multi-Objective Mixed-Integer Linear Programming
NGO	Non-governmental Organisation
OM	Operations Management
PO	Photochemical Oxidation
SCC	Supply Chain Collaboration
SCI	Supply Chain Innovation
SCM	Supply Chain Management
SCOR	Supply Chain Operations Reference
SCND	Supply Chain Network Design
SCS	Supply Chain Sustainability
SFO	Self Funded Organisation
SFSC	Sustainable Food Supply Chain
TE	Terrestrial Ecotoxicity

NOTATION

Indices

i	Index for farmers location, i = 1, 2, ..., I
j	Index for processing plant location, j = 1, 2, ..., J
k	Index for distributor/retailer location, k = 1, 2, ..., K
l	Index for waste recovery plant location, l = 1, 2, ..., L
m	Index for market location for recycled products, m = 1, 2, ..., M
t_1	Index for transportation mode (Mango), t_1 = 1, 2, ..., T
t_2	Index for transportation mode (Pulp), t_2 = 1, 2, ..., T
t_3	Index for transportation mode (Waste and Pectin), t_3 = 1, 2, ..., T
p	Index for time period (days), p = 1, 2, ..., P
a	Age of the mangoes procured in days, a = 1, 2, ..., SL_M
b	Age of the mango waste generated in days, b = 1, 2, ..., SL_{MW}

Economic-related parameters

Overall Transportation

TCM_{t_1ij}	Transportation cost per kg of mango from farmer i to processing plant j through transportation mode t_1
TCP_{t_1jk}	Transportation cost per kg of mango pulp from plant j to distributor k through transportation mode t_2
TCW_{t_1jl}	Transportation cost per kg of waste from plant j to waste recovery plant l through transportation mode t_3
TCR_{t_1lm}	Transportation cost per kg of recycled product from waste recovery plant l to market m through transportation mode t_3

Mango processing plant

FCP_j	Annual fixed cost for building and equipping processing plant j
VCP_j	Variable cost per kg for processing of mango at the processing plant j
PV_j	Maximum production volume (kg/day) of processing plant j
MQ	Quantity (kg) of mango required to produce one unit of mango pulp
CM_{pi}	Purchasing cost per kg of mango procured from farmer i in period p
HCW_j	Handling cost per kg of waste (peels, seeds) at the plant j
ICM_j	Inventory holding cost per kg of mango in processing plant j
ICP_j	Inventory holding cost per kg of mango pulp in processing plant j
QoP	Quantity (kg) of peels present per kg of mango waste

Waste recovery plant

FCR_l	Annual fixed cost for building and equipping waste recovery plant l
VCR_l	Variable cost per kg of recovery at the waste recovery plant l
PV_l	Maximum production volume (kg/day) of waste recovery plant l
$WQ]$	Quantity of mango waste (kg) required to produce one unit of recycled product
$ICMW_l$	Inventory holding cost per kg of mango waste in recovery plant l
$ICRP_l$	Inventory holding cost per kg of recycled product in recovery plant l
HCW_l	Handling cost per kg of mango waste at the plant l

Environmental-related parameters

Overall transportation

$EITM_{t_1ij}$	GHG emission associated with transportation of one kg of mango from farmer i to processing plant j through transportation mode t_1
$EITP_{t_2jk}$	GHG emission associated with transportation of one kg of mango pulp from plant j to distributor k through transportation mode t_2
$EITW_{t_3jl}$	GHG emission associated with transportation of one kg of waste from plant k to recovery plant l through transportation mode t_3
$EITR_{t_3lm}$	GHG emission associated with transportation of one kg of recycled products from recovery plant l to market m through transportation mode t_3

Mango processing plant

EIP_j	GHG emission associated with the processing of one kg of mango at the plant j
EIM_i	GHG emission associated with the cultivation of one kg of mango at the farm i
$EIIM_j$	GHG emission associated with holding inventory of mango (kg) in processing plant j
$EIIP_j$	GHG emission associated with holding inventory of mango pulp (kg) in processing plant j
$EIMW_j$	GHG emission associated with mango waste (kg) in processing plant j

Waste recovery plant

EIR_l	GHG emission of recovery one kg of mango waste at the waste recovery plant l
$EIIMW_l$	GHG emission associated with holding inventory of mango waste (kg) in recovery plant l
$EIIRP_l$	GHG emission associated with holding inventory of recycled product (kg) in recovery plant l
$EIMW_l$	GHG emission associated with mango waste (kg) in waste recovery plant l

Social-related parameters

$JOPP_j$	Number of fixed job opportunities created from opening mango processing plant j
JO_{pj}	Number of job opportunities created from processing of one kg of mango in processing plant j
JOW_j	Number of job opportunities created from handling one kg of wastes at mango processing plant j
JOW_l	Number of job opportunities created from handling one kg of wastes at waste recovery plant l
$JOWP_l$	Number of fixed job opportunities created from opening a new facility for mango waste recovery l
JO_l	Number of variable job opportunities created per kg of mango waste recovery l
JO_{t_1ij}	Number of job opportunities created from the transportation of one kg of mango from farmers i to processing plant j
JO_{t_2jk}	Number of job opportunities created from the transportation of one kg of waste from processing plant j to distribution centre k
JO_{t_3jl}	Number of job opportunities created from the transportation of one kg of waste from processing plant j to recovery plant l (n per unit quantity)
JO_{t_3lm}	Number of job opportunities created from the transportation of one kg of waste from recovery plant l to market m (n per unit quantity)
$JOInv_j$	Number of job opportunities created from handling one kg of waste in processing plant j
$JOInv_l$	Number of job opportunities created from handling one kg of waste in waste recovery plant l

Other parameters

D_{pk}	Demand for mango pulp (kg) from the distributor k in period p
D_{pm}	Demand for the recycled product (kg) from the market m in period p
M	Maximum number of mango processing plant to open
N	Maximum number of waste recovery plant to open
CF_{pi}	Capacity of the farmer (kg) i to supply mango in period p
SL_M	Shelf life (days) of mango
SL_{MW}	Shelf life (days) of mango waste
$MaxIM_j$	Inventory storage capacity (kg) for mango in processing plant j
$MaxIM_j$	Inventory storage capacity (kg) for mango pulp in processing plant j
$MaxIW_l$	Inventory storage capacity (kg) for mango waste recovery plant l
$MaxIRP_l$	Inventory storage capacity (kg) for the recycled product in waste recovery plant l

Decision variables

y_j	Binary variable takes the value of 1 if processing plant j is selected; 0 otherwise
z_1	Binary variable takes the value of 1 if waste recovery plant l selected; 0 otherwise
m_{pt_1ij}	Quantity (kg) of mangoes transported with t_1 from farmers i to processing plant j in period p
p_{pja}	Quantity (kg) of mango pulp produced at processing plant j using mango of age a in period p
tp_{pt_2jk}	Quantity (kg) of mango pulp transported with t_2 from processing plant j to distributor location k in period p
w_{pj}	Quantity (kg) of waste (peels and seeds) generated from the processing of mango at processing plant j in period p
tw_{pt_3j1}	Quantity (kg) of waste transported with t_3 from processing plant j to waste recovery plant l in period p
r_{plb}	Quantity (kg) of recycled product produced at waste recovery plant l using mango waste of age b in period p
tr_{pt_31m}	Quantity (kg) of recycled product transported with t_3 from recovery plant l to market m in period p
$invm_{pja}$	Quantity (kg) of inventory of mango of age a in processing plant j in period p
$invp_{pj}$	Quantity (kg) of inventory of pulp in processing plant j in period p
$wastem_{pja}$	Quantity (kg) of mango goes waste after reaching its shelf life $a = SL_M$ in processing plant j at the end of period p
$invmw_{plb}$	Quantity (kg) of inventory of mango waste in recovery plant l with age b in period p
$invrp_{pl}$	Quantity (kg) of inventory of recycled product in recovery plant l in period p
$wastmw_{plb}$	Quantity (kg) of mango waste goes as unusable for recovery after reaching its shelf life $b = SL_{MW}$ in waste recovery plant l at the end of period p
m_{pja}	Quantity (kg) of mango of age a available at the beginning of period p in processing plant j
mw_{plb}	Quantity (kg) of mango waste of age b available at the beginning of period p in waste recovery plant l