Multi-Criteria Evaluation Based Solutions for the Sustenance of the Non-Centrifugal Sugar Industry

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B. Sravya (2018PHXF0033H)

ABSTRACT

Non-centrifugal sugar (NCS, also known as Jaggery) industry is one of the oldest agro-based small-scale cottage industries in India, operated and manned by local farmers. The NCS production involves the 4 main sub-processes viz. juice extraction, juice clarification, juice evaporation and NCS drying. Over the decades, the NCS production processes adopted by these farmers are crude, energy inefficient, and technically unchanged, which resulted in the continual downfall of the NCS industry and its market, despite the well-proven nutritional, medicinal and other favorable features of NCS.

In order to sustain the NCS industry, it becomes essential to address these drawbacks and bring out the necessary solutions in a more scientific way. One possible pathway in this direction is to identify the most suitable technologies among different available technologies for different sub-processes in the NCS production line. This process of choosing the right technology is a complex problem governed by several mutually conflicting criteria covering resources, environmental effects, technical, economic and process output parameters, etc. Multi-criteria evaluation (MCE), a scientifically proven and well-established tool which had been used by several researchers over the decades for several such problems, could be seen as an appropriate tool for solving this kind of problem. Motivated by this, the main objective of the undertaken research works in this thesis is to bring out MCE based solutions for the sustenance of the NCS industry w.r.t. techno-economics, resource utilization, environmental impacts and process output parameters.

Extensive field and literature studies have been conducted to finalize (a) the criteria covering the aforementioned parameters (b) alternative technologies for each of the sub-processes (c) the applicable MCE tools, that are suitable for the present research problem. The identified alternative technologies for each sub-processes were analyzed by using 7 applicable MCE tools. These MCE tools are (a) Analytical hierarchy process (AHP), fuzzy Analytical hierarchy

process (FAHP), Shannon entropy method for weights estimation and (b) Technique for order preferences by similarity to ideal solution (TOPSIS); Preference ranking organization method for enrichment evaluations II (PROMETHEE II); *Vlsekriterijumska optimizacija i kompromisno resenje* (VIKOR) and Elimination et choix traduisant la realité I (ELECTRE I) for assessment of the alternatives. The required data for the MCE is sourced from extensive field, literature and experimental investigations as applicable.

MCE was performed for juice extraction process with 11 criteria on 6 alternatives. Criteria weights computed indicate that capital cost, energy costs and quantity of juice are the most important and influential criteria in identifying the suitable juice extraction techniques for NCS production. “Crusher with a single horizontal roller that uses an electrical motor without any usage of hot water” is found to be the most sustainable juice extraction method. On the other hand, the current practice of using “crusher with single vertical roller that runs on electrical energy without usage of hot water” and “crusher with single horizontal roller that runs on diesel engines without the usage of hot water” is a comparatively least preferred alternative for NCS production.

A similar MCE analysis was carried out for juice clarification process using the elicited qualitative data, with 11 criteria on 5 alternatives. Initial investment and extent of organic clarifiers are the most important criteria in identifying the suitable method of clarification for improving the quality and shelf-life of NCS. “Clarification with plant mucilage” is found to be the most appropriate and sustainable method. On the other hand, the “conventional practice of using inorganic clarifiers” as per the food standard limit can be used as a secondary option.

MCE on juice evaporation technologies was conducted for 10 alternatives based on 11 criteria. Capital cost, followed by heat utilization efficiency and quantity of NCS produced, are found to be the most essential criteria in identifying the sustainable juice evaporation method for production of NCS. “Single pan with the improved furnace” is found to be the most

suitable technology for juice evaporation process. On the other hand, the current practice of using, “single pan operated with traditional furnace” can be an alternative option only when the first preferred alternative is unavailable for any reason.

Experimental investigations was carried out to identify the most suitable process conditions for producing quality NCS w.r.t. the measured parameters related to quantity of reducing sugars, moisture content, hardness, color, taste, energy required, process time, cost. The MCE performed using this data from the experiments indicate that the NCS produced at 120^{o}C with no clarificants is the most suitable option among 12 samples generated at various combinations of striking temperature and clarification methods. The consequential result of this portion of the analysis is that the plant mucilage option for the clarification is the second-best option while “no usage of the clarificants” is the first option.

MCE on drying technologies for NCS was performed on 4 drying technologies using 9 criteria, indicates, capital cost, energy cost and greenhouse emissions are among the important criteria in identifying suitable NCS drying techniques for NCS production. Heat pump dryers is the most suitable option to get the desired moisture content (of less than 5%) to increase the shelf life of NCS during storing. The current practice of open sun drying is the next best technology for drying NCS.

The consolidated outcome of undertaken research works indicates that the NCS production line comprised of (a) a single horizontal crusher with no usage of water, (b) no clarificants (c) a single pan evaporation unit with a modified furnace design (d) heat pump dryer is the most appropriate process line for the sustenance of the NCS industry.

Keywords: *Non-centrifugal sugar (MCE), Multi-criteria evaluation (MCE) techniques, Analytical hierarchy process (AHP), Fuzzy analytical hierarchy process (FAHP), Shannon entropy method, TOPSIS, PROMETHEE II, VIKOR and ELECTRE I.*

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LIST OF ABBREVIATIONS

NCS	Non-centrifugal Sugar
AHP	Analytical hierarchy process
CAC	Carbon activated clarification
CI	Consistency index
CR	Consistency ratio
DT	Drying technology
EC	Electrocoagulation
ELECTRE I	Elimination et choix traduisant la realité
ET	Evaporation technology
FAHP	Fuzzy Analytical hierarchy process
IOC	Inorganic clarification
MCDM	Multi-criteria decision making
MCE	Multi-criteria evaluation
MFC	Membrane filtration
MHEN	Multi-horizontal roller operated on electrical energy without usage of hot water
MHEY	Multi-horizontal roller operated on electrical energy with usage of hot water
PMC	Clarification by plant mucilage
PROMETHEE II	Preference ranking organization method for enrichment evaluations
RCI	Random consistency index
SC	Sub-criteria
SHDN	Single horizontal roller operated on diesel engine without usage of hot water
SHEN	Single horizontal roller operated on electrical energy without usage of hot water
SshHEN	Shedder with single horizontal roller operated on electrical energy without usage of hot water
SVEN	Single vertical roller operated on electrical energy without usage of hot water
TOPSIS	Technique for order preferences by similarity to ideal solution
VIKOR	Vlsekriterijumska optimizacija i kompromisno resenje

LIST OF SYMBOLS

C_a	Net Concordance index
CC_j^*	Relative closeness of alternative
D^* & D^-	Ideal positive & ideal negative value
D_a	Net Discordance index
d_{ij}	Element of normalized decision matrix
E_j	Entropy of statistical variance
E_j	Entropy value of criteria w.r.t alternative
m	Number of alternatives
n	Number of criteria
Ø	Net outflow ranking
p_{ij}	Element of decision matrix
Q_j	VIKOR index
R_{ij}	Statistical variance
S_i & R_i	Utility measure & regret measure
S_j^* & S_j^-	Separation measure from ideal positive & ideal negative
v_{ij}	Elements of weighted normalized decision matrix
W_i	Integrated weights
w_i	Weights of criteria
W_o	Objective weights
W_s	Subjective weights
λ_{max}	Maximum eigen value

1. Introduction

Keywords

Non-centrifugal sugar

Gur

Jaggery

Multi-criteria evaluation

> *"According to the medical testimony I have reproduced in these columns, Gur is any day superior to refined sugar in food value, and if the villagers cease to make Gur, as they are already beginning to do, they will be deprived of an important food adjunct for their children. They may do without Gur themselves, but their children cannot without undermining their stamina. Gur is superior to bazaar sweets and to refined sugar,"* **Gandhiji** wrote in ***Harijan*** in 1935.
>
> This thesis is on the research works undertaken to suggest solutions to the problem envisaged by Gandhiji almost 90 years ago.

1.1. The non-centrifugal sugar (NCS)

Non-centrifugal sugar (NCS), generally called as jaggery, is a natural sweetener produced by concentrating sugarcane juice, without subjecting it to centrifugation and without separation of molasses. *Table 1.1* presents the complete composition of NCS (Abhai Kumar and Singh 2020). The color of NCS varies from golden brown to dark brown and a good quality NCS contain more than 70 % sucrose, less than 10% of simple sugars (glucose and fructose) and 5 % minerals, 3 % moisture, along with fats, proteins, and phosphorus and also accumulate large amount of ferrous (iron) during its preparation in iron vessel (Pattnayak and Misra 2004). The range of mineral and nutritional components is 5 times higher than that in brown sugar and 50 times higher than that in white sugar (Longvah et al. 2017). Therefore, NCS is regarded as one of the healthier and essential sweetening agents for human consumption. Although, Food and Agriculture Organization (FAO) of the United Nations recognized NCS as distinct and healthier form of sugars in 1964 itself, it took another 43 years for the World Customs Organization (WCO) to recognize it as unique and healthier form of sugars(FAO 1994).

Table 1.1 Composition of NCS (Abhai Kumar and Singh 2020)

Constituents	**Composition**
Sucrose	72-78gm
Fructose	1.5-7gm
Glucose	1.5-7gm
Magnesium	70-90mg
Potassium	1056mg
Calcium	40-100 mg
Phosphorus	20-90 mg
Sodium	19-30mg
Iron	10-13mg
Manganese	0.2-0.5mg
Zinc	0.2-0.4mg
Copper	0.1-0.9mg
Vitamins	A-3.8mg, B1-0.01mg, B2-0.06mg, B5-0.01mg, B6-0.01mg, C-7mg, D2-6.5mg, E-111.3mg
Protein	280mg
Calories	383kcal
Water	1.5-7gm
Protein	280mg

According to the ancient Indian traditional medicine, Ayurveda, it is salubrious to regularly consume NCS for the following scientifically proven health/medicinal benefits (P. Jagannadha et al. 2007):

- NCS is composed of longer chains of sucrose compared to refined sugar. As a result, it releases energy more gradually than sugar and provides energy for long period which is preferable for human body.
- Due to the fact that NCS is manufactured in iron vessels, a sizable volume of ferrous salts (iron) is also acquired during the process, which is good for human consumption, especially for those who are iron-deficient or anemic.
- NCS also contains traces of mineral salts which are very beneficial for the body. Mineral salts present in NCS leaves a hint of salt on the tongue. These salts come from the

sugarcane juice where it is absorbed from the soil.

- NCS is very good as a cleansing agent to clean lungs, stomach, intestines, esophagus, and respiratory tracts and hence regular consumption of this NCS could keep away the diseases related to these human organs (e.g., dust allergies asthma, cough and cold, congestion in the chest, indigestion etc.).

Having realized these advantageous and healthier features of NCS, it is processed in approximately 25 nations, with an annual production of 13 million tons. Indian Subcontinent, Southeast Asia, and Africa are the main markets for NCS consumption (Shrivastava and Singh 2020). Globally, India has been among the top with 55% of production and consumption of NCS produced from cane followed by Colombia, which accounts for 11%. NCS market located in Muzaffarnagar , Uttar Pradesh, India is the oldest and largest NCS market in the world, followed by NCS market located in Anakapalle , Visakhapatnam District of Andhra Pradesh, India (Indian sugar mill association 2019). Even though India still maintains this distinction, there has been a continuous decline in the production and consumption of NCS in India, leading to the failure of the Indian NCS industry. According to the available statistics (a) the percentage of cane used for producing NCS has come down from 59.5 % in 1950-51 to 32.5 % in 2003-2004 with corresponding quantities for sugar being 19.6% to 56.1 %; (b) The amount of NCS produced has come down from 76.63 million metric tons (MMT) in 1990-91 to 44MMT in 2020-2021; (c) The per capita consumption of NCS has steadily come down from 13.74 kg/annum in 1975-76 to a mere 4.2 kg/annum in 2017–18, while there has been an increase of this quantity for sugar from 6.06 kg/annum to 18 kg/annum (India Sugar Annual GAIN Report 2021). All these clearly indicate the inimical shift of sweetener demand from healthy NCS to unhealthy sugar leading to the downfall of the once well-established NCS Industry. The reasons for this unfavorable trend could be multitude. Specific to India and to a greater extent, some of these are: primitive, inefficient, energy intensive production processes and technologies resulting in increased energy and production costs, unfavorable economies for all the stakeholders in the supply chain, lack of established support policies and structures, very limited access to the world markets, worldwide unawareness about the advantageous features of NCS and many more.

Process wise, the NCS production process line is quite simple that involves (a) juice extraction, (b) juice clarification, (c) juice evaporation, (d) NCS drying, (e) molding, packing, and storage (as shown in *Figure 1.*)(Rakesh Kumar and Kumar 2022). However, the technologies/techniques for each subprocesses, being practiced in several hundreds of cottage units across India, are quite ancient and unchanged for several decades, energy-inefficient with lower productivity, human labor-intensive, all resulting in increased cost of production (Dutta D 2015). All these suggests to investigate on the above barriers to bring out solutions to sustain the NCS and its Industry in India to promote the use of the NCS, thereby contributing to the sustenance of the rich food heritage of India.

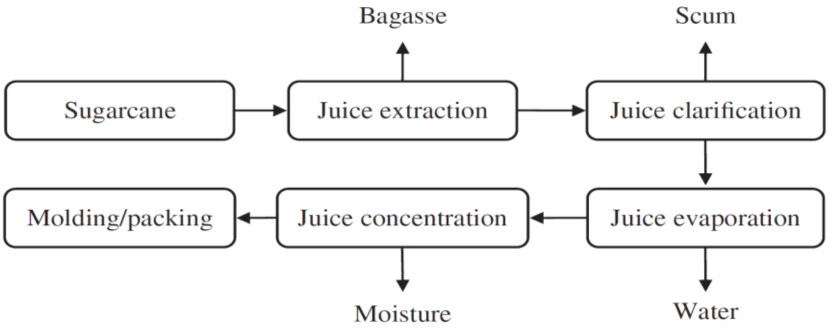


Figure 1. 1 Traditional NCS production process

The sustenance of the NCS and its industry is dependent on the sustenance of these individual sub-processes. In the conventional practice, many technologies are available for each sub-process involved in NCS production. However, these technologies/techniques are quite ancient and unchanged for several decades and may not be sustainable (Tyagi et al. 2022). Toward transforming these inferior techniques for sustenance of NCS industry, it is necessary to identify and select sustainable technique among the existing technologies at various stages in the production process. Given that, sustainability in manufacturing any product is defined as “The creation of manufactured products that use processes that (a) conserve energy and natural resources (b)reduce negative environmental impacts, (c) are economically sound and (d) are safe for employees, communities and consumers”(Moldavska and Welo 2017), the process of identification and selection of sustainable techniques should satisfy the above mentioned sustainability elements in term of technical superiority, economic viability, environmentally favorability, that leads to optimized process output parameters with a lesser demand for resources. These sustainability criteria themselves are functions of several sub criteria, respectively, which suggest that arriving at a sustainable process requires simultaneous optimization of all these criteria involved. Therefore, to identify and arrive at the right technology for the sustenance of NCS and its industry by satisfying the above mention sustainability criteria, multi-criteria evaluation (MCE) / muti-criteria decision making (MCDM) techniques can be used as a decision support tool.

Motivated to work towards sustenance of NCS and its industry, work presented in this thesis were aimed at identifying the sustainable line for NCS production using MCE techniques. The steps taken to complete each stage of the research work are detailed in this chapter. A brief overview of the thesis' chapters can be found in this chapter as well.

1.2. Thesis outline

The outline of the thesis, chapter wise, along with a brief description is as follows:

Chapter 1 presents the over view on NCS and its production process. Also, highlights the basic information related to the research topic of the present thesis.

Chapter 2 presents a detailed review of literature on the historical perspective of NCS industry. The chapter starts with a brief discussion on the traditional NCS production process followed by detailing the technological improvements for each and every sub-process and associated economic, commercial and allied elements. Finally, the research gaps identified from the published works of aforementioned elements of the NCS production process are presented.

Chapter 3 presents the possibility to use multi criteria evaluation techniques to bring out solutions that could fill the identified research gaps. The chapter starts with a brief discussion on the fundamentals of MCE and its techniques. Also, presented are, the details on the application of MCE techniques in various domains and its relevance to the present problem in hand. Based on research gaps identified in the previous chapter, the working objectives were proposed and presented. Finally, the chapter ends with the scope of present research work.

Chapter 4 presents the MCE model and analyses for selection of sustainable and suitable juice preparation technologies viz. juice extraction and juice clarification processes for NCS production. A comprehensive understanding of existing technologies and current practices for juice extraction and juice clarification process units is presented. A detailed explanation on a wide range of evaluation criteria for these process units covering sustainability elements is also presented. The type of stakeholders group considered and their importance in providing the data for these process units are also detailed. Finally, the detailed discussion on the outcomes of undertaken MCE analysis for identifying the sustainable juice extraction and clarification process has been presented.

Chapter 5 presents the MCE model and analysis for selection of sustainable juice evaporation technology and process conditions for NCS production. The first section of this chapter provides a comprehensive understanding of existing juice evaporation technologies and its associated governing criteria covering sustainability elements to identify a sustainable juice evaporation technology for the NCS industry. Subsequent sections of this chapter contain the experimental procedure to obtain the required data for identifying the correct process conditions in terms of temperatures, concentration and other parameters.

Chapter 6 presents the MCE model and analysis for selection of sustainable and suitable drying technology to produce quality NCS. This chapter provides a comprehensive understanding of existing and applicable new drying technologies and associated governing criteria covering sustainability elements to identify a sustainable drying technology to produce quality NCS. Finally presented the detailed discussion on the outcomes of undertaken MCE analysis for identifying the sustainable drying technology for the NCS industry.

Chapter 7 presents the overall conclusions of the research work presented in the thesis and recommendations for future work.

2. NCS Industry: Evolution, Evaluations and Research Opportunities

Keywords

Non-centrifugal sugar

Juice extraction

Juice clarification

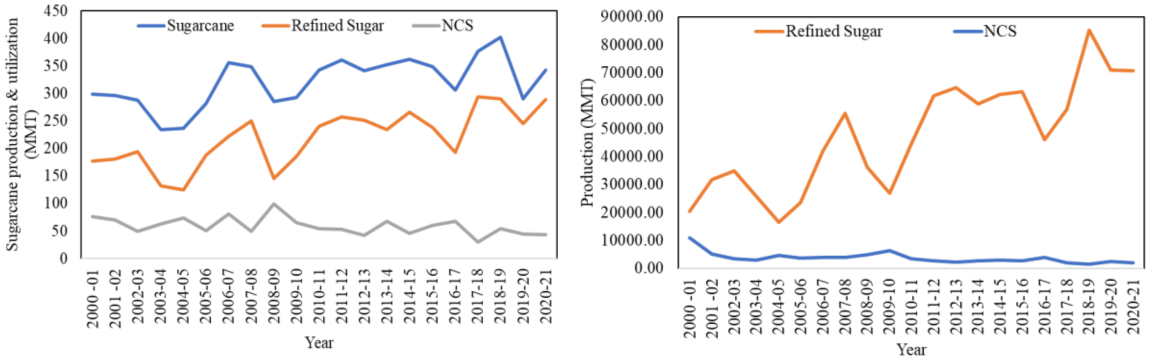
Juice evaporation

NCS drying

NCS industry is one of the ancient, largest, unorganized rural-based cottage industries in India. As it will be presented in the following sections, even though the technology and art of making of NCS is several decades old, the literature survey reveals that very limited scientific works have been reported. The reported works on technological aspects of NCS production disclose that technological features of NCS production have not changed much for the last several decades. Most of these cottage industries still rely on energy-inefficient, labor-intensive, crude and primitive methods to produce NCS. Added to these are, economic models and supply chain management activities that promote the role of middlemen, depriving economic benefits to the producer and health benefits to the final consumer of NCS, all these contributing to the failure of this once well-established NCS industry. The following sections of this chapter present a narration of techno-economic-commercial developments related to NCS production and use. This chapter ends with a description of research gaps identified through this literature review exercise.

2.1. NCS industry - studies and developments

The Indian NCS industry is the largest unorganized sector which is one of the most ancient and important rural-based cottage industries in the country (Madan HK 2004). With a minimal capital investment, this industry provides employment to 2.5 million people in rural regions while providing around 40 % of the world's sweetener needs(Anwar A. 1999). Over the past few decades, the utilization of sugarcane for NCS and production of NCS have been taken over by its competitor's white sugar. *Figure 2.1* shows these trends (GAIN 2020).



(i) (ii)

Figure 2. 1 (i) Utilization of sugarcane for NCS production (ii) Production of NCS (GAIN 2020)

Sugarcane is the important raw material which accounts 88% of the total variable cost in NCS production (Teggi M.Y. 1998). Generally, in India the NCS production starts in September /October and continues till March/ April and is stored for the rest of the year (Kumar D 2013). The reason for seasonal production of NCS is due to seasonal yield of sugarcane. In India, the sugarcane crop typically matures between 10 to 12 months in the northern states and 12 to 16 months in the southern states depending upon the season of the crop (Gangwar, Solomon, and Anwar 2015). While, in principle, NCS can be produced from any variety of sugarcane, researchers have identified a few varieties viz. Co 313, Co 421, Co 475, Co 508, Co 775 BO 70 CoJ 64, CoC 671, BO 91, CoS 8432, CoS 8436, CoLk 94184, CoLk 9709 more suitable varieties.

The production of NCS is a continuous process of heat and mass transfer in which fresh sugarcane juice and bagasse are used respectively as raw material and fuel. The well-established traditional production process of NCS (*Figure 2.2*), involves a number of operations such as juice extraction, juice clarification, evaporation in single, or multi-pan units, drying/concentration of juice followed by molding, packing, and storage (Velásquez et al. 2019). Extraction of juice is usually done by crushing the sugarcane in a power operated (engine/electric) vertical/horizontal crushers (Shrivastava and Singh 2020). The extracted juice from the sugarcane is collected in a masonry settling tank, which separates the heavier impurities under the process of plain sedimentation. Then the juice is limed to precipitate out impurities and prevent inversion sucrose into other sugars. Further, the juice is clarified using organic/inorganic clarifiers to remove soluble and insoluble impurities to improve the quality of NCS. Then the cleared sugarcane juice is transferred into the boiling pan where it is continuously heated and stirred. The continuous heating and stirring of sugarcane juice in an open pan, boiles off water from the juice to striking temperature of 110-120°C and transform the sugarcane juice from liquid to semi-solid, which after cooling becomes solid.

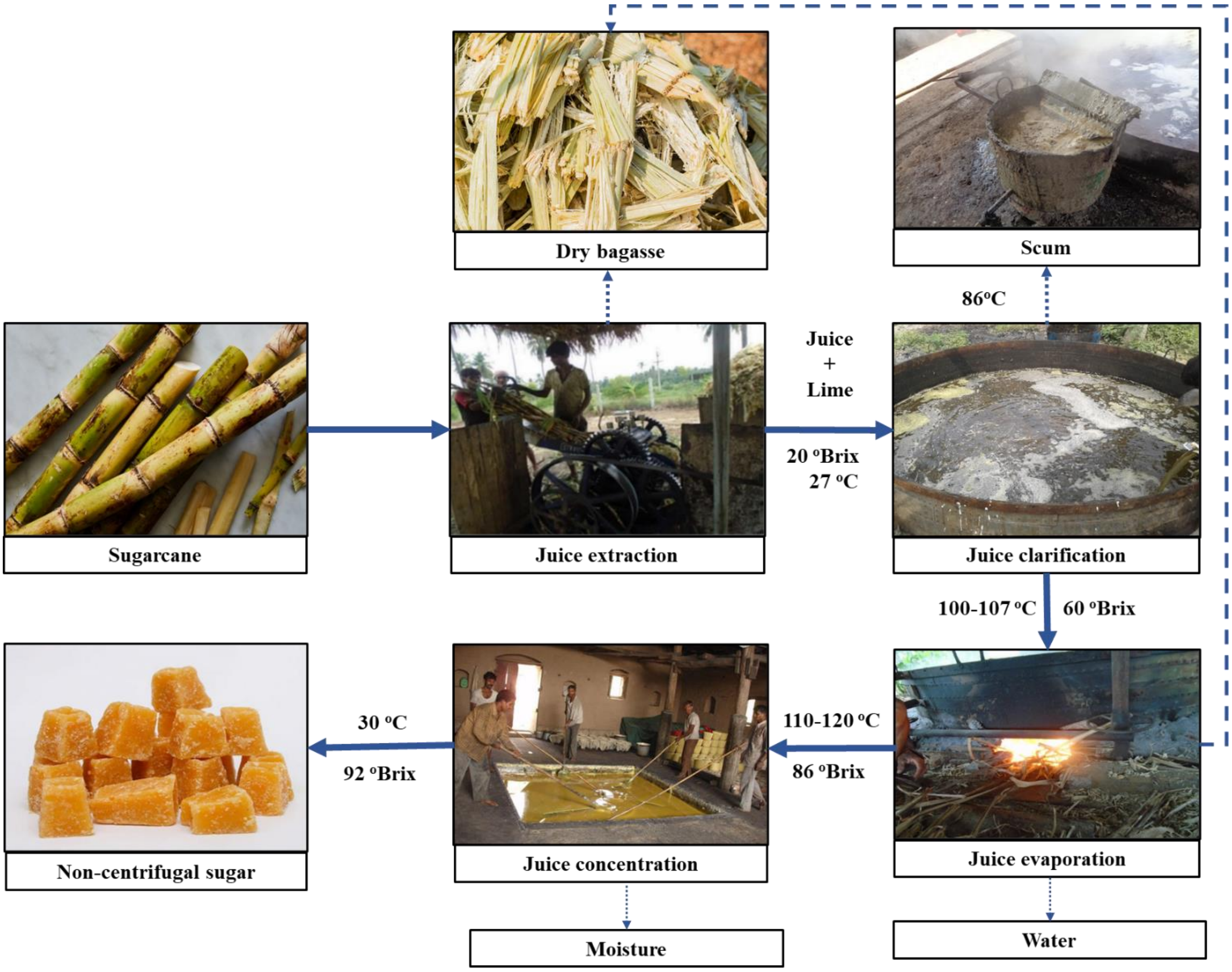


Figure 2.2 Traditional NCS production process (Source: Field studies)

(i) Juice extraction

Extraction of sugar cane juice (by crushing the sugar cane in a crusher) is the primary and critical process in the production of NCS, usually done by crushing the sugarcane in a power operated (engine/electric) vertical/horizontal crushers. In the current practice the sugarcane is manually fed into the crusher to get the maximum amount of juice. The quantity and the quality of juice extracted depends on the type of crushing method adopted. The quality of juice is defined in terms of brix and usually in a freshly extracted juice it ranges about 20°Brix. *Figure 2.3* illustrates the different crushing methods adopted for extracting the juice for NCS production at various NCS production units viz. Anakapally, Andhra Pradesh, India; Marayoor, Kerala, India and Erode, Tamil Nadu, India, respectively. That were captured during field visits.


Horizontal roller crusher operated on electrical energy

Vertical roller crusher operated on electrical energy

Horizontal roller crusher operated on diesel engine

Figure 2.3 Representative pictures of juice extraction process (Source: field studies)

In conventional technologies for juice extraction of NCS production, typical values of extraction efficiencies vary from 50 to 55 % (for vertical crushers) and 55 to 60 % (for horizontal crushers) (P. Jagannadha Rao, Das, and Das 2007). The bagasse produced during this extraction process is sun dried and used as fuel in the subsequent evaporation process. The bagasse obtained from current practice of crushing the sugarcane typically contains 45 to 50 % moisture due to poor crushing efficiency.

(ii) Juice clarification

The extracted juice from the sugarcane is collected in a masonry settling tank, which separates the heavier impurities under the process of plain sedimentation. Then the juice is limed to precipitate impurities and prevent inversion of sucrose into other sugars. up. *Figure 2. 4* illustrates the complete process of clarification method adopted at one of the NCS production units in Anakapally, AndhraPradesh, India, observed during field visits.

Addition of inorganic clarificants

Manual stirring for scum removal

Scum removed to obtain the clarified sugarcane juice

Figure 2. 4 Representative pictures of clarification process

(Source: field visits at Anakapally, AndhraPradesh, India).

From *Figure 2. 4*, it can be observed that the process of clarification is done totally manual. The freshly extracted sugarcane juice contains pH 5.2, which forms invert sugar during boiling of juice. In order to prevent the inversion of sugars, lime is added manually to sugarcane juice to balance the pH of sugarcane juice. The so formed scum after liming is removed manually with help of long ladles. The addition of lime results in dark color NCS, this undesirable color NCS and reduces the market value. Therefore, to substantiate the color, hydros are added manually to make it clear and good color NCS. The major problem with the use of chemical clarifiers is that there is no well-prescribed level of clarifier usage and there is always a possibility of adding these chemicals beyond the safety confines for human consumption. Sulfur dioxide is the most common clarifier that results in sulfates and organic sulfur that are dangerous for human beings. Traditionally, some vegetable juice like Deola (Hibiscus ficulneus), Bhindi (Hibiscus esculentus), Sukhlai (Kydia calycina), Bark of Semal (Bombax malabaricum), Bark of Falsa Tree (Grewia asiatica), Groundnut (Arachisypogea), Castor Seed (Ricinus communis) are used for the removing the scum. However, in some areas, the traditional additives have been replaced by certain chemicals, such as the lime water, phosphoric acid and calcium oxide (Rakesh Kumar and Kumar 2018).

(iii) Juice evaporation

In production of NCS, juice evaporation is one of the most essential and important process. The clarified sugarcane juice is transferred into a single or multiple open pan(s) which receive heat from hearths below. Through this heating process, the juice is heated up to 110-120 ^{o}C, while being stirred continuously. The bagasse obtained during juice extraction is used as fuel in the furnace. During evaporation the maximum amount of water present in the juice is evaporated. The concentrated semi-liquid NCS in terms of brix ranges from 80 to 85 ^{o}Brix. The gradual heating and stirring of sugarcane juice in an open pan transforms the sugarcane juice from liquid to semi-solid and reaches to 90^{o} brix.

Figures 2.5 and 2.6 illustrate the juice evaporation method adopted at traditional NCS production units at Anakapally, Andhrapradesh and Marayoor, Kerala, India, respectively. It can be observed that a traditional single open pan is placed on a furnace below the ground level. The heat from the furnace to the pan is transferred mainly through convection and radiation. The furnace used for this evaporation unit is made of ordinary masonry bricks and mud at NCS production unit in Anakapally, Andhrapradesh, India, while earth clay and mud at Marayoor, Kerala, India. One end of the furnace is open for the flow of flue gases with a continuous draft. This evaporation method requires comparatively less capital cost and has a relatively less heat utilization efficiency of 14.7 %.


Sun dried bagasse as fuel for juice evaporation

Manual addition of bagasse to furnace for combustion

Chimney for the escape of flue gases produced during combustion of bagasse

Figure 2.5 Representative pictures of juice evaporation process
(Source: field visits at Anakapally, AndhraPradesh, India).

Sun dried bagasse as fuel for juice evaporation

Manual addition of bagasse to furnace for combustion

Chimney for the escape of flue gases produced during combustion of bagasse

Figure 2.6 Representative pictures of juice evaporation process
(Source: field visits at Marayoor, Kerala, India).

In all NCS production units bagasse is used as a fuel. The efficient combustion of bagasse depends upon the percentage of moisture content (Rakesh Kumar and Kumar 2018). The percentage of bagasse in sugarcane varies from 23 % to 37 % depending upon the variety of sugarcane used (Agarwal A 2013). Open sun drying of bagasse is a traditional method used in all NCS productions which can decrease the moisture content from 50 % to 20 % (Rao KSS 2003). The presence of moisture and volatile matter not only decrease the thermal efficiency of the system, but also releases large amount of un-burnt gases such as CO_2, N_2, O_2, H_2O, CO, NO_x, SO_2, volatile organic compounds, and particulate matter which could be harmful to humans and the environment. However, non-availability of the bagasse to meet the energy demand forces the NCS manufacturers to go for cheaper alternative fuels such as used tyres which results in higher values of SO_2. Similarly, higher moisture in auxiliary fuels used during startup of the furnace is too high to support combustion, then SO_2 and NO_x emissions will increase.

In all NCS production units bagasse is used as a fuel. The efficient combustion of bagasse depends upon the percentage of moisture content (Rakesh Kumar and Kumar 2018). The percentage of bagasse in sugarcane varies from 23 % to 37 % depending upon the variety of sugarcane used (Agarwal A 2013). Open sun drying of bagasse is a traditional method used in all NCS productions which can decrease the moisture content from 50 % to 20 % (Rao KSS 2003).

(iv) NCS drying

Drying of NCS is the final and crucial sub-process in NCS production. The main objective of this process is to remove the excess moisture content in NCS that improves the shelf-life of NCS while storing. In the process of drying of NCS, heat is transmitted from the environment to the surface of the NCS, where it is used for both sensible heating to raise the temperature of the NCS surface and latent heat of vaporization to drive away any moisture that may be present in NCS. The quality of NCS after the drying process reaches to 90-95^{o}brix. *Figure 2.5* illustrates the conventional practice of drying NCS. In this process, the concentrated sugarcane juice after the evaporation process is transferred into an empty pan and is continuously stirred with the help of long ladles manually. Then it is left to open atmosphere and to remove the left-over moisture present in the NCS. NCS produced from this method of drying contain moisture above 5 %, which is undesirable for long-term storing as it affects the quality and reduces the shelf-life of NCS. It is reported that, in India, every year, more than 10% of NCS worth \$0.6 million is lost owing to moisture deterioration (Rakesh Kumar and Kumar 2018).

Transferring the concentrated NCS syrup from boiling pan

Concentrated NCS syrup

Stirring the concentrated NCS syrup

Final NCS

Moulding & sun drying

Open sun drying

Figure 2.5 Conventional drying of NCS (Source: Field studies)

The technologies/techniques practiced in several hundreds of cottage units across India for NCS production are quite ancient and unchanged for several decades. These crude, unchanged, energy inefficient, technologically inferior production techniques result in higher production cost, leading to continues downfall of the NCS market in India over the last few decades despite nutritional, medicinal and other favorable features of NCS.

2.1.1 Technological aspects

Probably because of limited focus on research work aiming to improve the process lines, the published literature on the technical aspects of NCS production process are not that widely available. These reported works mainly concentrated on thermal engineering aspects, mainly focusing on the evaporation processes/ moisture removal processes with in NCS production. However, all these have reported sporadic improvements in the existing technologies/techniques for one or two sub-processes in isolation. Further, these works, with their focus on one or two sub-processes, have limited success in transforming the entire production process for improved productivity and energy efficiency. Further, there are hardly any published works specifically aimed at studying the sustainability aspects of the NCS production process for sustenance of NCS and its industry. In the present sections, some of the reported works that are specifically aimed at improving the conventional techniques of NCS production are presented.

Extracting jaggery from cane is quite ancient in India, probably during the first millennium BCE. In rural India, the sugarcane is crushed in a machine called a yantra, a large mortar and pestle turned by animals such as bullocks, camels, and so on. From the last two to three decades, these animal-powered crushers have been replaced by diesel engines and/or electric motors (P. Jagannadha Rao, Das, and Das 2007). Traditionally, till now, sugarcane is manually fed into the crusher to extract juice, which is labor-intensive, time-consuming, and prone to accidents. To reduce the possibility of these accidents and time, Hasarmani developed a solar photovoltaic system to control the electric motor used for sugarcane crushing, which helped to lessen the carbon footprint of the NCS industry(T.Hasarmani 2018). Dauda Musa et al. in 2014 reported that the crusher for juice extraction is featured with three vertical or horizontal cylindrical rollers as shown in *Figure 2.6* (Dauda Musa et al. 2014). One of the rollers is corrugated, while the other two have minute cuts on their surfaces that put pressure on the sugarcane to extract the juice and also assist with feeding. *Figure 2.6* presents the front and side view of the horizontal cylindrical rollers. Extraction efficiencies of such conventional crushers vary from 50 to 55 % for vertical crushers and 55 to 60 % for horizontal crushers.

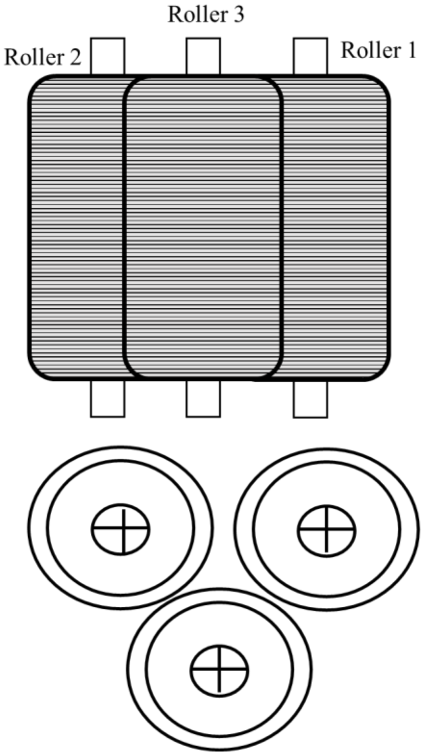


Figure 2.6 Schematic view of three roller sugarcane crusher (Dauda Musa et al. 2014)

The quality of NCS is defined by the type of clarificants used and the clarification method adopted. In traditional practice of NCS making, sulfur dioxide (Hydros) is the most commonly used clarifier and the so formed scum is removed manually. Which may result in the production of sulphates and organo-sulfur that are dangerous for human consumption(Verma, Shah, and Mahajani 2019). In order to improve the quality of NCS with minimum or no hazard to human consumption, Jegatheesan et al. evaluated the membrane technology for juice clarification by passing the juice under pressure through sequence of membrane filters to remove the settable solids present (Jegatheesan et al. 2012). The use of this membrane filtration results in better quality clarified juice with better clarity, significantly lower viscosity, and considerable colour reduction while reducing or eliminating the need of chemicals, particularly lime. Similarly, Chikkappaiah et al. (2017) have studied effect of five plant mucilage viz. aloe vera, flax seeds, fenugreek, purslane and malabar spinach as a clarification agent for NCS production. This plant mucilage was taken at different concentrations of 0.1 %, 0.2 % and 0.4 % of raw sugarcane juice. Aloe vera at 0.4% concentration was shown to remove the maximum number of impurities from sugarcane juice with the shortest processing time. Likewise, Khan Chand (2015) investigated the application of activated charcoal for sugarcane juice clarification using the response surface method (RSM) and observed that temperature of 77.55 °C and a thickness of 1.5 mm activated charcoal and 0.4 g/L of deola (Hibiscus Ficulneus) are the ideal conditions. Also, olís-Fuentes et al., (2019) conducted a comparison between the quality of NCS made with bagasse activated carbon (BAC) and BAC with ultrafiltration. A white color NCS is produced, which is quite contrasting to usual golden yellow color. Ogando et al. (2019) studied the use of electrocoagulation as a replacement for the sulfitation-based sugarcane clarifying process(Ogando et al. 2019). The amount of total phenolic compounds, turbidity, and ICUMSA color were all dramatically reduced by electrocoagulation treatment and also clarification of sugarcane juice was improved by applying higher voltages.

Till early 1980s, NCS production used single pan (as shown in *Figure 2.7*), inefficient equipment that increased fuel use and environmental pollutants. To improve the thermal and heat utilization efficiency of a traditional NCS making plant, Baboo B, (1994) facilitated a second pan known as gutter pan in the path of hot flue gases following the boiling pan(Baboo B 1994). In an attempt to save the fuel consumption for NCS production, Rane MV, (2005) suggest a novel concept of a heat pump-based freezing Concentration System (FCS) to concentrate the sugarcane juice from 20 to 40 ^{o}brix (Rane MV 2005). Juice is delivered to a boiling pan for further concentration after flowing over a freezing surface that serves as both an evaporator and a condenser consecutively and saved 1338kg of bagasse for 1000kg NCS. Singh (2008) observed that the overall efficiency of two-pan furnace was improved up to 29.3 % and reduced the operating cost up to 34.82% when compared to traditional single pan furnace as shown in *Figure 2.8*(A. K. , B. B. and R. D. S. Singh 2008). Anwar modified the two-pan and single-pan NCS making plant by using fins at the bottom of boiling and gutter pans as shown in *Figure 2. 9* (Anwar 2010). In both the cases it was observed that better heat utilization efficiency and saving of bagasse and energy (i.e., two-pan and single-pan) were about 9.44%and 31.34% correspondingly. Sardespande et al. assessed the thermal performance of a four-pan NCS production unit and found that controlled fuel feeding of bagasse decreased the specific fuel consumption from 2.39 kg to 1.73 kg per kg of NCS(Sardeshpande, Shendage, and Pillai 2010). Manjare and Hole observed that the thermal efficiency of traditional two-pan NCS making plant is increased from 16.16% to 24.36% by implementing an economizer and pre-heater, also reduced the use of bagasse by 1.2 kg per kg production of NCS (Manjare and Hole 2016). Arya attempted to improve the performance of a three-pan NCS making plant and observed the increased in production capacity of jaggery (about 12%) respectively along with lesser emission and lower exhaust gas temperature (as shown in *Figure 2.10*) (Arya, Kumar, and Jaiswal 2013). Also, Anwar noticed an improvement in thermal efficiency up to 35%, fuel saving up to 26% and decrease in production time of NCS up to 30% per batch by fabricating an efficiency booster at the bottom of single pan NCS manufacturing plant (Anwar SI. 2014). Shiralkar et al. found that the thermal efficiency and bagasse consumption of multi-pan NCS manufacturing plant were 46% and 1.44 kg/kg of NCS with flow rate of air about 0.13m^{3}/s through the furnace (Shiralkar et al. 2014).

Jakkamputi et al. employed solar energy to pre-heat inlet air to 150°C, which resulted in a savings of 0.122 kg of dry bagasse per kg of NCS produced compared to traditional NCS making (Jakkamputi and Mandapati 2016). Madanrao observed the reduction in bagasse utilization from 3.83 kg to 2.75 kg per kg of NCS and the improved the thermal efficiency of the plant from 15.35% to 24.50% by using the fins at the bottom of boiling pan of a prototype model of traditional single pan NCS making plant (Madanrao RK 2017). An energy-efficient NCS production process was examined by Rane and Uphade in 2016 used a two-stage heat pump freeze pre-concentration technology. The system achieved a COP of 14 with a specific power consumption of 8.88 kWh/m^3 of water removal at evaporation, condensation, and heat rejection temperatures of -8 °C, 3 °C, and 34 °C, respectively (Milind v. Rane and Uphade 2016). Using a combination of heating and freezing pre-concentration, Srinvas et al. in 2019 evaluated the ideal amount of energy needed for jaggery production and found that reduction in energy consumption of 535.1 kJ/kg of juice (Srinvas et al. 2019).

Figure 2.7 Traditional single pan NCS production

Figure 2.8 Two pan NCS production

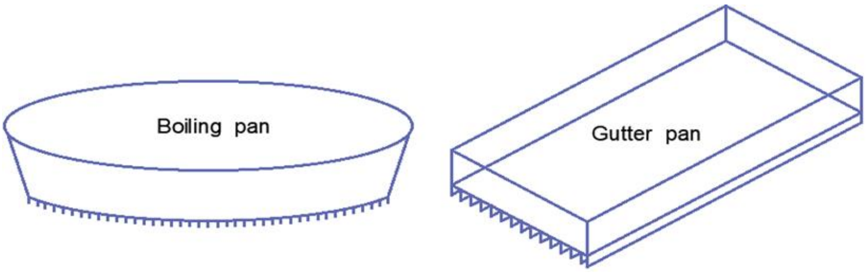


Figure 2. 9 Boiling and gutter pan with fins

Figure 2.10 Three pan NCS production

An attempt was made by Marie et al. in 2020 to investigate the energy requirements of a system incorporating a freeze-concentrator and a solar thermal heater to reduce the reliance on the combustion of bagasse or other fuels in a NCS production process and found a potential energy saving in excess of 38 MJ/kg NCS and a fuel saving of more than 2 kg of bagasse/kg of NCS produced (Marie et al. 2020). An exploratory work to use solar energy in evaporation sub processes of NCS production was attempted by Venkata Sai & Reddy in 2020 and concluded that solar option would be a better option to meet the energy needs of NCS production and saves 6.98 to 38.12 tons of bagasse (Venkata Sai and Reddy 2020). Through their studies on modified gutter pans with internal fitting of copper tubes as shown in *Figure 2.11,* Kumar et al. reported 65.52% thermal efficiency and a bagasse consumption of 1.50 kg/kg of NCS (Rakesh Kumar and Kumar 2021).

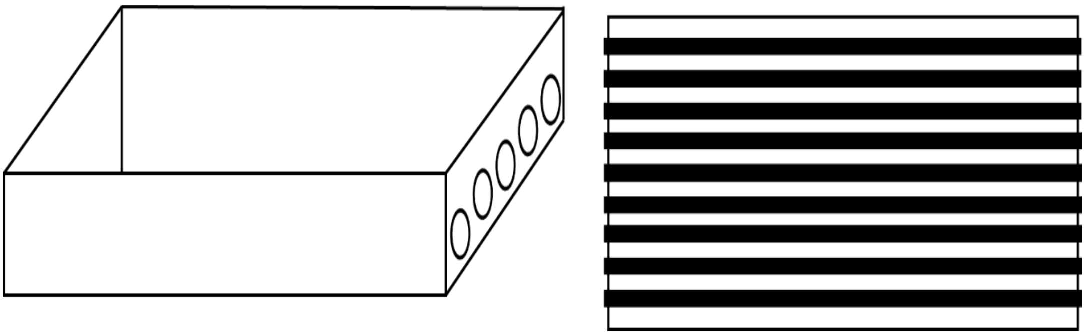


Figure 2.11 Schematic diagram of modified gutter pan (Rakesh Kumar and Kumar 2021)

Until now, in many of traditional NCS making process, concentrated NCS syrup formed after evaporation process is dried in open sun with continuous stirring with flat wooden scrapers. Kumar & Tiwari has developed a thermal model for estimating the hourly temperature of NCS, greenhouse air and moisture air under natural convection mode of NCS drying (Anil Kumar and Tiwari 2006). These models can be useful for designing the greenhouse dryer for a particular quantity of NCS with thin layer. Verma et al. have studied the influence of temperature and relative humidity on the drying characteristics of NCS and determine the optimum drying conditions (in terms of temperature and relative humidity) for different compositions of NCS (Verma, Shah, and Mahajani 2020). Raj et al. designed a minimal energy-intensive tunnel dryer to condense moisture content in the granular NCS below 3%. With (a) length, height and width of 18, 1.2 and 1 m respectively and (b) 18 trucks and 24 trays/truck, the drier requires 176.49 MJ of energy to dry 1 ton of NCS in 68 minutes (Raj et al. 2021).

2.1.2. Economic aspects

India is the world's largest producer and consumer of NCS. The production of NCS by small-scale cottage-based industry have a significant contribution in the rural economy of the country (J. Singh et al. 2011). Due to price risk, marketing issues, and lack of technological assistance, NCS production has declined in recent years, thereby affecting the economic benefits of rural area. The present section details some of studies on the economic implications of NCS production

Raju studied the costs and profits of NCS production and commercialization in East-Godavari area of Andhra Pradesh, India. Per hectare of sugarcane land, the cost of making NCS accounted to ₹. 28, 417. The price of producing sugarcane worked out to almost 70% of the entire cost (cost of raw material). Also, the wages paid to workers, the rent for using the crusher and the chemical additives were the other major cost elements. The expected gross and net returns of producing NCS per acre of sugarcane were ₹ 33,724 and ₹ 5,127, respectively (Raju 1989).

Similarly, Maheswarappa have undertaken a detail study on the cost of NCS production and marketing in Karnataka. Noted that the typical yield of NCS per hectare was 10 110.50 quintals. Also reported that the cost of clarificants and other incidental charges, the rental cost of the cane crusher, and the wages paid to workers, which were ₹. 3332.00, ₹. 1142.07, and ₹. 446.50 per hectare, respectively, were the three major cost components in the manufacturing of NCS (Maheswarappa 1998).

Lakshmi Prasanna, studied and compared the NCS production in small farms and large farms and reported that the break-even output of small (73.5 quintals) and large farms (57.96 quintals) are obtained be less than the average yield of NCS 87.47 and 84.78 quintals, respectively. Indicating that both the farms were profitable as they could yield more than their break-even production levels (Lakshmi Prasanna 1992).

Shivaramu examined the NCS production units in in the Talakaveri of Kodagu district in Karnataka, India to evaluate the triple pan NCS making furnace compared to regional varieties. It was noted that the net return was about 2-2.5 times higher with triple pan furnace i.e., around ₹ 1,22,000 per year than with local type viz. signal pan and double pan furnace with 51,000- 65,000/year, while the daily production rate of NCS using triple pan furnace was 11.5q and using local type furnace is 7-8q (Shivaramu 2002). Deokate et al. studied the cost of NCS production and marketing in Maharashtra and concluded that profitability of NCS production unit depends upon the efficient marketing (Deokate et al. 2010). However, NCS process unit are profitable when NCS is processed on others NCS unit on rent basis.

Dwivedi conducted a detail survey on 30 random NCS unit of Kushinagar district of Uttar-Pradesh and examined the cost-return analysis, profitability and operational efficiency. These selected NCS units are classified into three production units depending upon the production capacity. The production capacity of these small, medium and large NCS unit are 10, 11-25 & 26-30 quintals, respectively (Dwivedi 2010). The study revealed that small production unit can only make the bare minimal profit while the medium and large production units are more profitable that is more than 30%.

Alibaba studied the NCS production unit in Visakhapatnam district of Andhra Pradesh, India during 2001–2002 and work-out the benefit cost ratio to be 1.33. Also, revealed that between 2001 and 2002, the price of NCS is doubled while the profitability of its NCS production decreased. The increase in labor costs is one of the primary causes of this depreciation (Alibaba 2005).

Ramarao studied the NCS production unit in sugarcane growing region in Andhra Pradesh, India during 2008–2009 and examined various economic factors involved in NCS production. Reported that total investment for one of the well-established NCS production unit is ₹ 1,23,112. The economic analysis concluded that labour charges are major contribution to the variable cost that in turn increase the cost of NCS. Shortage of labour during peak operation time is one the major reason for increase in labour cost (Ramarao 2011).

Shivanaikar et al. conducted a detail survey on 9 random organic and inorganic NCS unit in Bagalkot district of Karnataka, India and examined the various economic factors involved in NCS production. Reported that total investment for both the well-established organic and inorganic NCS production unit is ₹ 4,38,875. The economic analysis concluded that labour charges and cost of inorganic are major contributors to the variable cost that in turn increase the cost of inorganic NCS production unit.

Shankar Kumbhar studied and examined the 25 random NCS production units in major cluster of Kolhapur district in Maharashtra. In the study, it was found that most the NCS production unit owners are dealing with a common problem, but the effects of these problems vary from one another. Transportation, high raw material costs, inadequate profit, and a lack of research and development are some of the major issues that were noted. Also reported that the overall profit was ₹ 8800 per day, the daily profitability ratio was 0.338, and the daily efficiency ratio was 1.33 (Shankar Kumbhar 2016).

2.1.3. Commercial and allied aspects

NCS industry is one of the oldest, largest, and most significant agro-processing industries in India. Majority of NCS production units are located in rural regions of India. This industry meets approximately 40% of global sweetener requirements while employing 2.5 million people in rural regions with minimal capital expenditure. According to reported literature, 8–10 million tonnes of NCS are produced from roughly half of the sugarcane grown in India (Devi 2014). Over 70% of the world's NCS production is made in India. Indicating that India is one of the leading producers and consumers of NCS in the world. NCS and substitute sweeteners worth more than ₹ 2,000 crore are shipped to a variety of nations, including the United States, Canada, the United Kingdom, the United Arab Emirates, Kuwait, Oman, the Philippines, Bangladesh, and USSR (former) etc.

Effective marketing is essential for NCS producers to be profitable. The colour, texture, and fragrance of the NCS have a significant impact on its market value. According to literature its noted that NCS producers are allegedly more profitable when selling NCS through cooperative societies. Generally, marketing of NCS involves number of middlemen’s starting from NCS producers to consumers through which the marketability of NCS is varied. The present section details some of studies on the commercial and allied aspects of NCS production.

Rohal studied price variation in marketing of NCS at Muzaffarnagar market of U.P., India and identified two marketing channels viz. (i) NCS producer – processor - primary wholesaler - secondary wholesaler - retailer – end costumers (ii) NCS producer - primary wholesaler - secondary wholesaler - retailer – end costumers. Stated that channel II was more effective than channel I as NCS producer's share in end costumer's rupee was high (Rohal 1990). Padmanabhan examined the performance of NCS marketing as well as potential for cooperative marketing by examining pricing efficiency, operational efficiency and price spread. Identified three important channels for NCS marketing (Rohal 1990; Padmanabhan K 1991).

Lakshmi Prasanna studied the price variation in Chittoor jaggery market, Andhra Pradesh, India and reported five NCS marking channels via. (i) NCS pproducer – commission agent – local wholesaler – local retailer – end costumers (ii) NCS producer - commission agent – Distant wholesaler – retailer – end customers (iii) NCS producer - commission agent – wholesaler cum exporter – end customers (iv) NCS producer – distant wholesaler – end customers (v) Consignment. Among all, channel 4 was confined to off-seasonal sales. Also, majority of the NCS sold at the Chittoor market was marketed through channel 3(Lakshmi Prasanna 1992) .

Babar examined the patterns of NCS arrivals and prices in the Sangli regulated market, Maharashtra. According to them, over the 12-year period, there was an increasing trend in both the arrivals and pricing of NCS on the market. While price indices increased in October, followed by August and September, the seasonal indices of NCS arrivals were greater from August to January (Babar 1994).

Teggi examined the marketing of NCS in Mudhol and Jamakhandi NCS markets of Ghataprabha command area of Karnataka. Three major NCS marketing channels were identified viz. (i) Channel I: NCS producer - commission agent - wholesaler - retailer – end customers (ii) Channel II: NCS producer - wholesaler - retailer - end customers (iii) Channel III: NCS producer - retailer – end customers. It noted that majority of NCS produced through these markets were marketed through channel II due to high price realized by NCS producer in respective channels (Teggi 1996).

Kurennvar studied the NCS marketing in Banglkot district of Karnataka' found that maximum percent of 53.75 sample farmers were disposing NCS through Channel I. The channel I involve number of middlemen from NCS produces to the end users viz. commission agents, wholesalers and retailers (Kurennvar s 2008).

Deokate et al. studying economics of production and marketing of NCS in Maharashtra identified the two channels in the sale of NCS viz. Channel I: NCS Producer -commission agent - wholesaler - retailer - end customers, Channel II: Producer - Co-operative sangh - wholesaler - retailer - end customers. Revealed that channel II had better marketing efficiency index and NCS producer contribution in end customers revenue.

Ramarao studied the NCS production unit in the sugarcane growing region in Andhra Pradesh, India during 2008–2009 and examined price spread NCS marketing. The reported study revealed prize spread of middlemen involved in the marketing the NCS from NCS producers to end customers during 2006-2009 (Ramarao 2011).

From all the above reported studies and other works imply that poor pricing policy, transportation and storage of NCS and sugarcane led to a long marketing channel and involvement of a large number of middlemen. Deficient credit from credit organizations at required time led the farmers/processors to get into contract with the commission agents by taking loans.

2.2. Research gaps and scope of the present research work

The aforementioned literature review reveals that, despite a host of benefits contributing to the rural industry development, better economic and social stature of small farmers and peasant communities, healthy society, NCS production and consumption has been undergoing a continuous decline, with its direct impact on the very sustenance of NCS industry. In order to revive this once very well-established rural cottage industry, it becomes essential to investigate all the reasons for this declining trend. The first step to address this is to focus on assessing how the existing NCS production technologies and the alternatives for the same could contribute for the sustenance of the NCS Industry. This could be done by analyzing different alternatives for different sub-processes with respect to different criteria related to techno-economics, resource utilization, environmental impacts and process output parameters. Such an analysis would suggest a better alternative for the current NCS production process line.

Given that, (a) the production of NCS involves four important and basic sub-processes viz. juice extraction, juice clarification, juice evaporation, NCS drying and (b) the sustenance of the NCS industry is dependent on the sustenance of these individual sub-processes, the research gaps that could be identified w.r.t to each of these sub processes are as follows:

- Juice extraction process: It is the very primary and essential processes that influence the quantity and quality of NCS produced. Field and literature studies indicate that currently adopted crushing technologies viz. horizontal and vertical roller crushers powered by diesel engines or electrical motors are the only technologies that are in practice for several decades. It is not clear if any alternate technologies serving the intended purpose are available, that may contribute to the sustenance of the NCS industry.
- Juice clarification: The reported literature on the aspects related to clarification is very sparse. It is not known if the current practice of using unhealthy inorganic clarifiers (such as Hydrose) could be replaced with more healthy alternatives. Even if such alternatives are available, it is not clearly known how to select the best option among these.

- Juice evaporation process: Water removal from the juice is the heart of the NCS production process. For the last several decades, it has been the practice to remove this water through evaporation using an open pan-underground furnace-bagasse (as a fuel) combination. Although the literature survey indicates that quite a few alternate technologies are available for this water removal, these are primarily aimed at improving a few process output parameters. It is not clear if these technologies could really be the better alternative(s) from the view point of techno-economics, resource utilization, environmental impacts and process output parameters.
- NCS drying: The edibility and use of the produced NCS depends on the effective moisture content of NCS. Open sun drying has been the conventionally followed practice for this. Literature survey indicates that there are hardly any reported works aimed to suggest alternatives for this, although there could be other established methods of drying.

The current research work is aimed to fill the above-mentioned research gaps and hence bring out solutions that contribute to the sustenance of the NCS industry.

3. MCE Tools to Analyze Technologies for NCS Production Sub-Process

Keywords

Multi-criteria evaluation

multi-criteria decision making

Analytical hierarchy process

FAHP

TOPSIS

PROMETHEE II

VIKOR

ELECTRE I

Multi-criteria evaluation (MCE) or multi-criteria decision making (MCDM) is a branch of operations research that helps the decision maker to solve and evaluate problems related to multiple criteria. Because of its ability to aid in the quality decision-making process in a more explicit, rational, and efficient way than traditional deliberative methods, MCE has become more popular in recent times. The fundamental aspects of the MCE, its applications in various areas and the possibilities to use these techniques to fill the research gaps identified in the previous chapter are presented in this chapter. This chapter ends with the objectives and scope of the present research work.

3.1. Fundamentals and basic steps of MCE

MCE is the scientifically proven, well established and extensively used decision making tool to solve complex decision problems governed by multiple criteria with single/multiple objective(s) (Abhishek Kumar et al. 2017). In contrast with the classical optimization techniques, MCE has the capabilities to handle a relatively large number of criteria while simultaneously handling their influence on the final decision outcome, in terms of their relative weightages, their qualitative & quantitative nature, maximization & minimization nature and crisp & fuzzy nature (Azhar, Radzi, and Wan Ahmad 2021).

Ever since the 1960's, MCE theories have emerged as an active area of research and resulted in several books and papers that are both theoretical and applied insights. Till date, there were more than 4712 papers addressing the application of MCE techniques in various disciplines. Given the advantages of MCE, it has been applied in wide variety of applications ranging from agriculture resource management (Hayashi 2000), sustainability energy management (Wang et al. 2009), defence(Sennaroglu and Varlik Celebi 2018) , health care(Adunlin, Diaby, and Xiao 2015) , material selection(Anojkumar, Ilangkumaran, and Sasirekha 2014), and so forth. The published works indicate that MCE methods provide a compromise solution to the problem by satisfying several conflicting criteria simultaneously in selecting a suitable method from a defined number of alternatives (Korhonen, Moskowitz, and Wallenius 1992).

Figure 3.1 demonstrates the basic steps involved in MCE method for selection of suitable alternatives. First step towards analysing the decision problem in MCE is defining the decision context. Followed by this, is the process of identifying the alternatives and decision criteria that govern the decisions. Decision criteria are the essential elements that significantly impact the selection of an appropriate alternative (Soltani et al. 2015). These decision criteria must be complete, nonredundant, mutually exclusive, and should be minimum (Kaya and Kahraman 2010). The next step after identification of decision criteria is determining the criteria weights. For the weight's estimation, the relative importance of the criteria estimated using the data on the criteria themselves or the performance of the data w. r. t each option, which is presented in the form of pairwise comparison matrix, would be used. Followed by this, would be aggregating the performance of the options (in the form of a data matrix) with respect to the chosen criteria and the weights of the criteria. This is then followed by ranking of the alternatives according to the assessment values obtained using MCE assessment methods. The source for forming the data matrix could be literature works, experimental analyses, theoretical analysis, field studies and combinations of these. The very next step is to check the consistency in the ranking patterns. If the ranking pattern is consistent, the best alternative for the objective is identified. Otherwise, decision ranks obtained are subjected to additional analyses using techniques such as geometric mean method and then the best alternative is identified. With all these, it can readily be identified that each and every step in MCE is mutually beneficial with complementary output (Nutt et al. 2014).

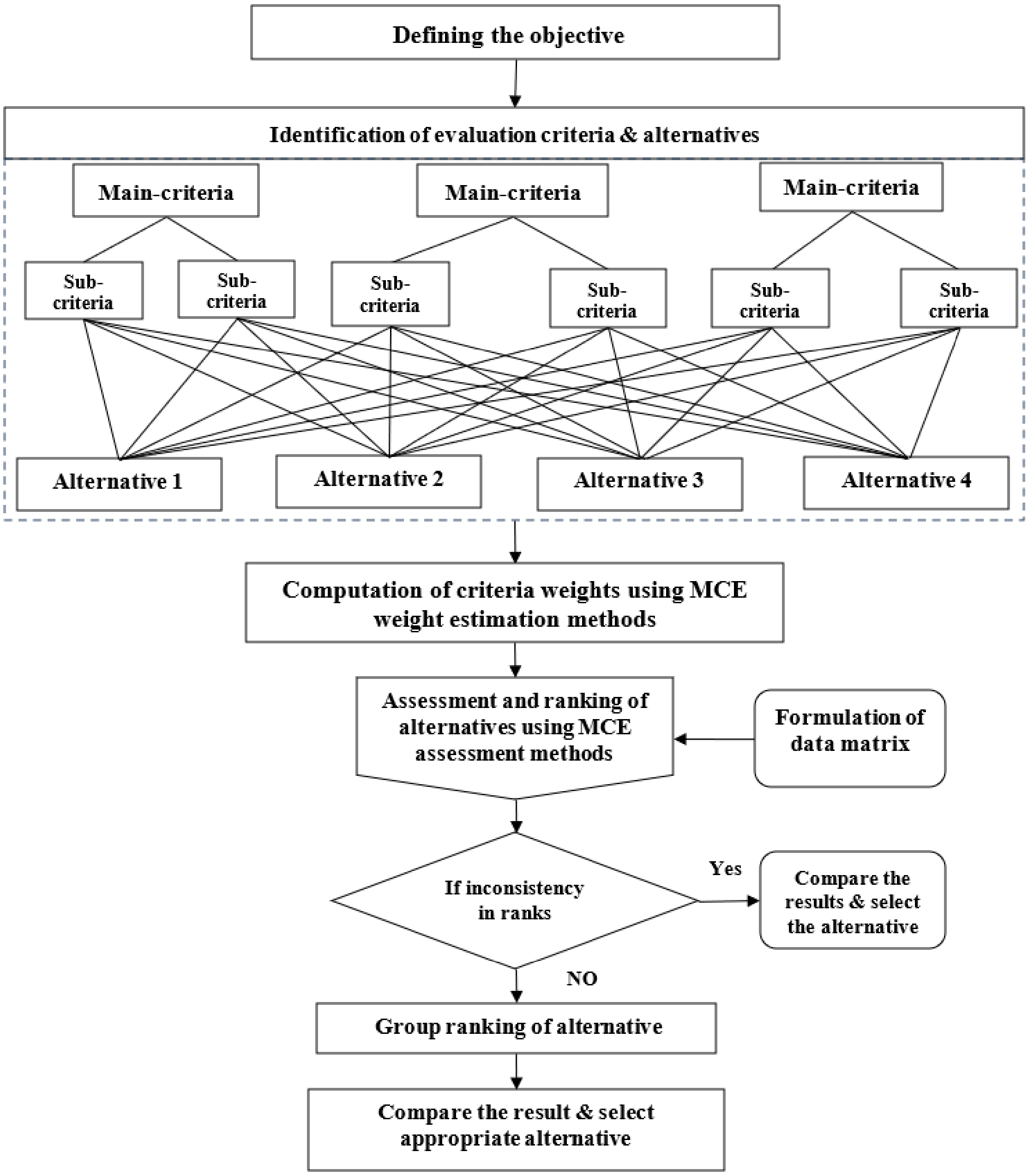


Figure 3.1 Basic steps involved in MCE

Over the years, many distinct MCE techniques and methodologies have been proposed, each with a unique theory, type of research questions it answers and the nature of results obtained. Some of the classical, well-established and documented methods of MCE are AHP, TOPSIS, PROMETHEE II, VIKOR, ELECTRE I (Mardani et al. 2015; Stojčić et al. 2019). These mentioned MCE methods have been effectively implemented in wide variety of application ranging from material selection to health care management, business management etc. (Ho and Ma 2018; Kubler et al. 2016; Behzadian et al. 2012; Raman Kumar et al. 2021; Behzadian et al. 2010; Yazdani and Graeml 2014; Figueira JR 2012). *Figure 3.2* presents the incidence of various MCE techniques over the last 20 years (Azhar, Radzi, and Wan Ahmad 2021). It can be observed (from *Figure 3.2*) that, among all the MCE techniques, AHP and FAHP are the most applied techniques followed by hybrid MCE. Hybrid MCE is referred to as the integration of two MCE methods that is one for weight computation and other for assessment and ranking of alternatives. For example, AHP-TOPSIS, where AHP is for computation of criteria weights and TOPSIS is used for assessment and ranking of alternatives. Following sections detail some of the well-established and documented methods of MCE.

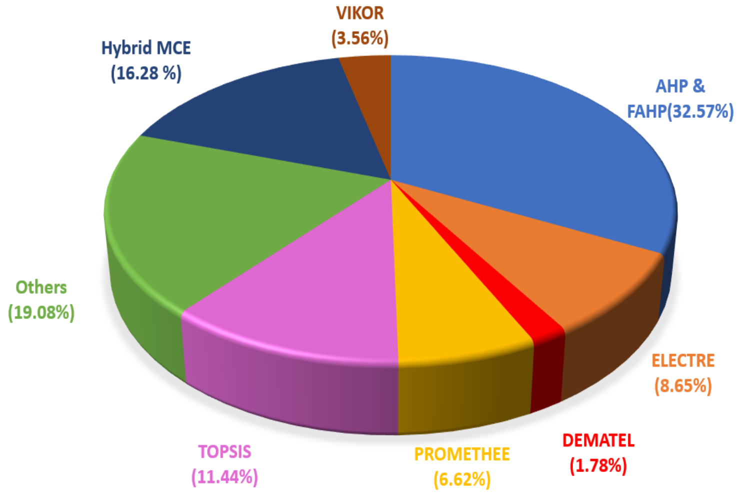


Figure 3.2 Incidence of various MCE techniques (Azhar, Radzi, and Wan Ahmad 2021).

3.2. Weight estimation methods

In selecting appropriate alternatives using MCE, evaluation of criteria weights has a significant impact on the outcome of final decision making and alternatives ranking (Triantaphyllou et al. 1998; Odu 2019; Cinelli, Coles, and Kirwan 2014). Therefore, it is necessary to determine these criteria weights accurately. In general, the two extensively used approaches to obtain the criteria weights are (a) subjective weight approach and (b) objective weight approach (Alemi-Ardakani et al. 2016). The determination of subjective weights depends on the opinion and subjective preference of qualified decision-makers with theoretical and practical expertise. However, any potential ambiguity in expert judgment or opinion may influence the decision-making outcome and lead to inappropriate selection of alternatives (Zavadskas and Podvezko 2016). The objective weight approach is based on the statistical assessment of data provided in the data matrix without considering the expertise and experience of the decision-makers, which may deviate from the results from the practical situation (Al-Aomar 2010; Zavadskas and Podvezko 2016). AHP, FAHP & entropy are among the well-established and extensively used methods by the scientific community in the last few decades(Kubler et al. 2016; Russo and Camanho 2015). Following are the details of these weight estimation methods.

3.2.1. Analytical hierarchy process (AHP)

AHP is extensively applied in decision-making problems to calculate criteria weights based on the decision maker's priorities (Cinelli, Coles, and Kirwan 2014; Russo and Camanho 2015). Proposed by Saaty in 1997 (Saaty 1977). In this method, the multifaceted decision problem is organized with a hierarchy of two or more levels. The primary and essential objective of the decision problem is placed at the first level, followed by the evaluation criteria and the alternatives (Khaira and Dwivedi 2018). It reduces the bias in decision-making by checking the consistency in priorities given by the decision makers against each evaluation criteria. On the other hand, this approach may not be suitable when decisions given by decision-makers are incomplete, imprecise, and fragmented (Emrouznejad and Marra 2017). This approach is complex when there are large sets of criteria(Macharis et al. 2004).

Figure 3.3 illustrates the procedural steps involved in computing the criteria weights using AHP. In this method, the multifaceted decision problem is organized with a hierarchy of two or more levels. In the decision hierarchy, the primary and essential objective of the decision problem is placed at the first level, followed by the evaluation criteria and the alternatives (Khaira and Dwivedi 2018). Another main requirement to obtain criteria weights using this method is to have a pairwise comparison of all criteria. Saaty's scale of relative importance is used to produce this pairwise comparison matrix by comparing one criterion over another (Saaty and Katz 1990). These 1 to 9 scales enable the decision-makers to assign how many times more or less one criterion is preferred over the other. The weight of evaluation criteria is computed based on this pairwise comparison matrix and their level of consistency is tested by means of consistency ratio (CR). In the event of inconsistency, the decision-maker is directed to revise the elements of matrix to arrive at better consistency and for which the criteria weights are recalculated (Saaty 2008).

AHP is extensively applied in MCE weight estimation method to calculate criteria weights based on the decision maker's priorities(Saaty 2008). Since its development, AHP has received substantial study and is applied in practically all applications related to MCE due to its simplicity, usability, and great adaptability. Liberatore & Nydick, 2008 examined 50 journal publications that used AHP in the field of medicine and healthcare and were published during 1981 to 2006 (Liberatore and Nydick 2008). Sipahi & Timor 2010 examined 232 journal publications from the years 2005 to 2009 and determined that AHP applications are predominant in the field of manufacturing (Sipahi and Timor 2010). Subramanian &

Ramanathan 2012 examined 291 journal publications that used AHP techniques in operations management published between 1999 and 2009 (Subramanian and Ramanathan 2012). Also, reported three main observations viz. (i) supply chain management and product and process design were the most discussed decision problems (ii) applications of integrated AHP methods in operations management are more common than stand-alone AHP (iii) applications of AHP in the manufacturing sector got greater attention than those in the service sector. Also, it is identified through various literary works that application of integrated AHP with other MCE methods is tremendously increasing year wise in various fields of study. This wide application of AHP is due to its easy applicability to complex decision problems that involve multiple criteria, subjective evaluation, and its successful combination with other MCDM techniques (Wen, Liao, and Zavadskas 2020).

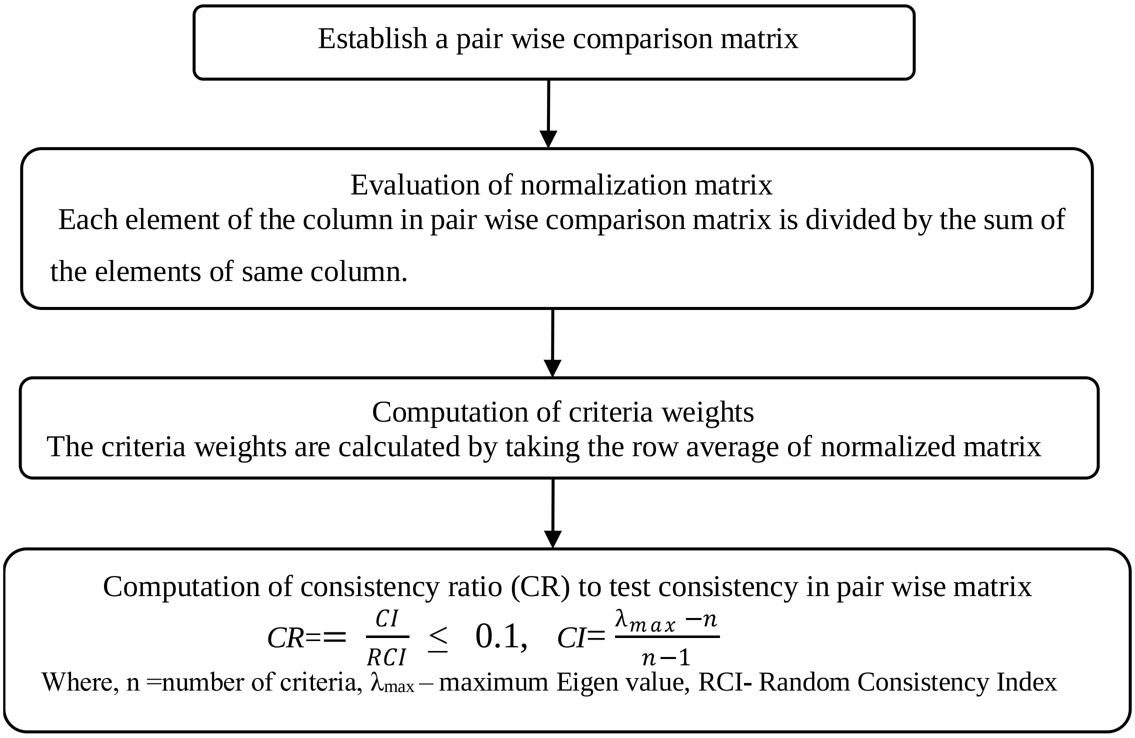


Figure 3.3 AHP procedure for evaluating the criteria weights (Saaty 1977)

3.2.2. Fuzzy analytical hierarchy process (FAHP)

In this method, primarily a FAHP model is established by arranging the objective at the first level of hierarchy, evaluation criteria at the second level and alternative at the third level. Like the classical AHP, FAHP also requires a pairwise comparison matrix of all the criteria to get criteria weights (Blin 1974). Saaty's nine-point scale of relative importance is used for generating this pairwise comparison matrix by comparing each criterion with the other (Saaty 2008). Whenever there is a fuzziness involved in the data (since some of the criteria are fuzzy in nature and the decisions given by the stakeholders could be incomplete, imprecise and fragmented), in FAHP, the pairwise comparison matrix is fuzzified using fuzzy membership functions (Kubler et al. 2016).

In 1983, Laarhoven & Pedryczt in 1983 proposed the first FAHP method by using triangular fuzzy numbers in the pairwise comparison matrix (van Laarhoven and Pedryczt 1983). *Figure 3.4* illustrates the procedural steps involved in computing the criteria weights using FAHP. Several additional strategies were put forth, employing a variety of fuzzy number types, including the trapezoidal membership function (Chen, Lin, and Huang 2006; Kaya and Kahraman 2010) or the less common bell-shape/gaussian membership function. Then, the geometric mean method of (Buckley, Feuring, and Hayashi 2001) could be used to build a comprehensive pairwise comparison matrix and to compute the criteria weights. Based on this aggregated pairwise comparison matrix, the criteria weights are computed.

FAHP is the second most widely used method after AHP for criteria weight calculation. In several studies, including Beskese et al. in 2015; Ghoseiri in 2014; Kubler et al. in 2016; Nazari et al. in 2012 (Kubler et al. 2016; Beskese et al. 2015; Ghoseiri 2014; Nazari, Salarirad, and Bazzazi 2012), FAHP has been examined as a potential solution to the MCDM problem. In these studies, a variety of factors, including social, geological, economic, and political and government positions were considered. Ju et al., (2012) present an FAHP-based evaluation index method for the emergency reaction capabilities, utilising 2-tuple linguistic factors that greatly ease the decision makers' comprehension of the generated scores (Ju, Wang, and Liu 2012). On the basis of FAHP, Jaganathan et al. proposed a group decision support method to assess innovative manufacturing technologies (Jaganathan 2007). In order to calculate a global sustainability score, FAHP-based assessment method can be applied (Abhishek Kumar et al. 2017).

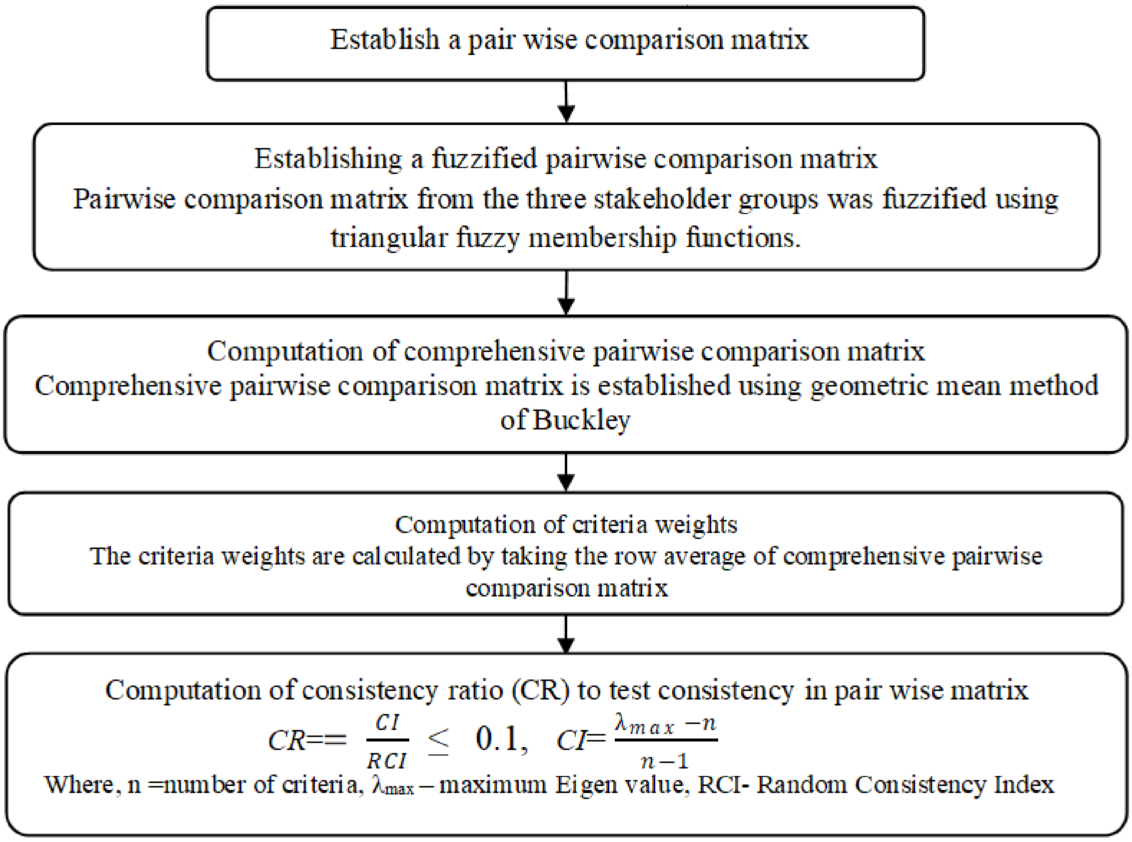


Figure 3.4 FAHP procedure for evaluating the criteria weights

3.2.3. Shannon’s Entropy method

Shannon’s entropy is given by Shannon in 1948 (Shannon 1948). The determination of objective weights by the entropy method is based on information theory, in which the criteria weights are derived objectively from the data matrix. This method of calculating objective criteria weights is extensively used when the judgment or the preference given by the decision-maker is partial and imprecise (Lotfi and Fallahnejad 2010). The significant benefit of this approach is its objectivity. The assessment of alternatives is based on a given criterion that decides its relative significance without direct interference of the decision-maker (Çalişkan et al. 2013) . *Figure 3.5* procedural steps involved in computing the criteria weights using Shannon’s entropy. The computation of objective weights of decision criteria is based on the performance value of alternatives with respect to each criterion presented in the data-matrix. The data-matrix is normalised using the standard normalization method to convert different units of various criteria into a common measurable unit. Based on the normalized data-matrix statistical variation is computed and the entropy of statistical variation is calculated. Finally, objective weights of decision criteria are computed based on the entropy of statistical variation.

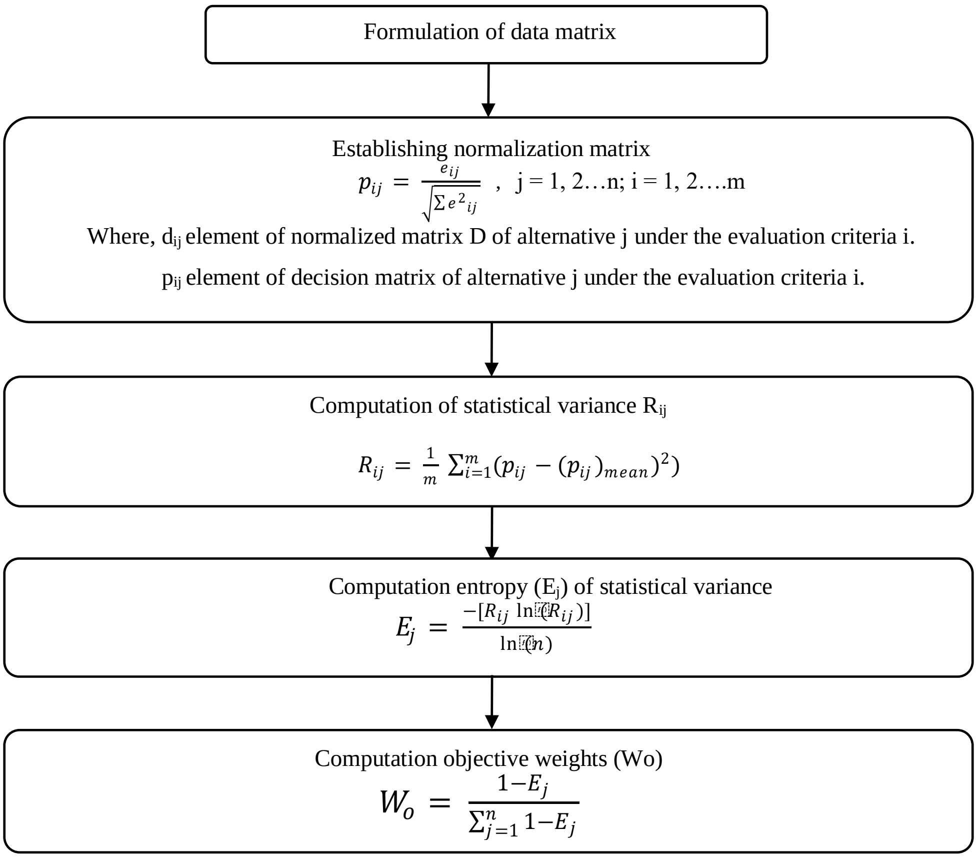


Figure 3.5 Shannon’s entropy procedure for evaluating the criteria weights (Shannon 1948)

3.3. Aggregation methods

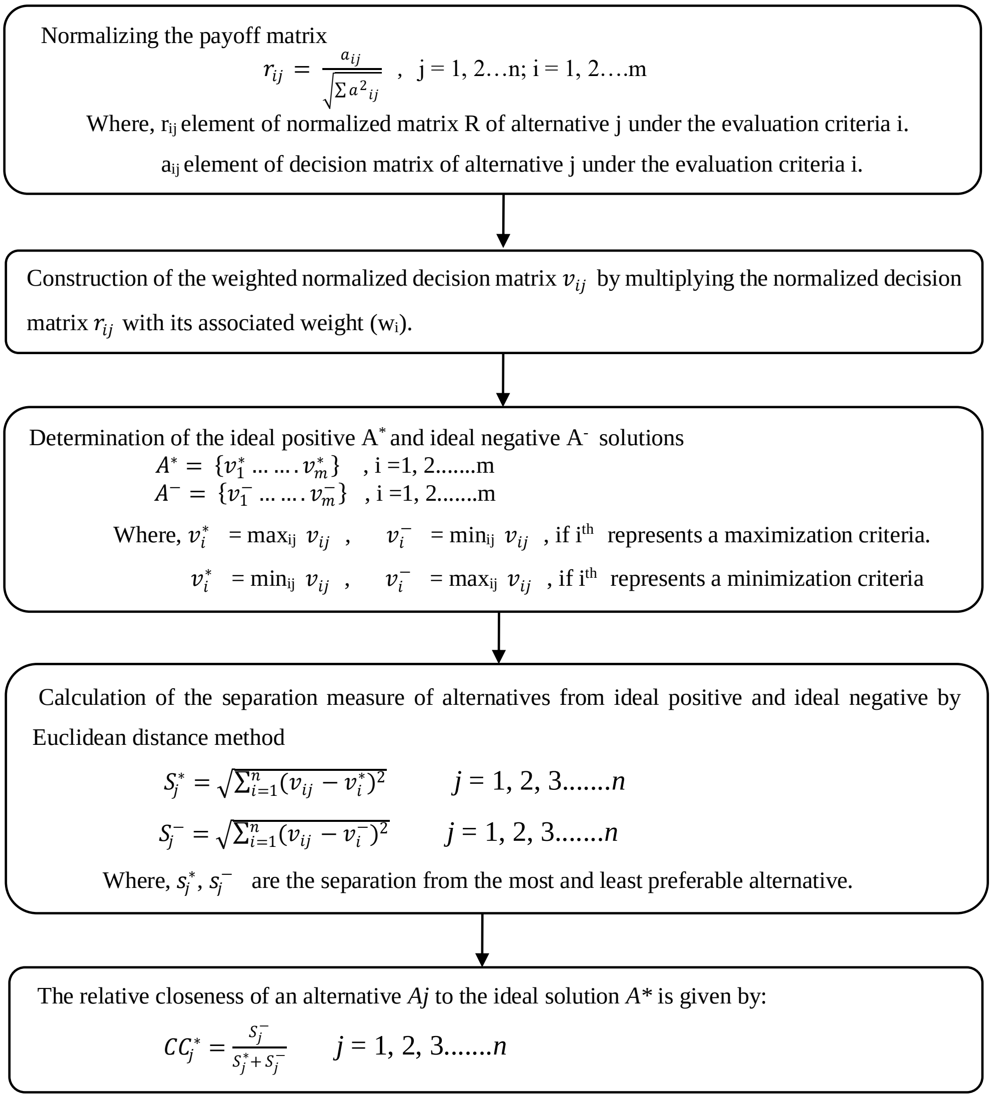
Generally, the MCE aggregation methods can be categorized either as multi-attribute utility theory (MAUT) or outranking methods. The MAUT methods include TOPSIS & VIKOR and the outranking methods include ELECTRE I and PROMETHEE II (Sotoudeh-Anvari 2022; Mardani et al. 2015). In MAUT, the assessment value of the alternative is obtained by normalizing the data matrix and aggregating the performance value of each alternative for each criterion. An outranking method is based on paired comparisons of alternatives for each criterion, and outranking relations are generated by aggregating the pairwise comparisons. Consequently, the variety of normalising techniques and aggregation functions used is the primary factor that contributes to the potential for distinct results from different MCE methods. The following sections present the details of these MCE aggregation methods (B. Roy 1996; Wen, Liao, and Zavadskas 2020).

3.3.1. Technique for order preferences by similarity to ideal solution (TOPSIS)

TOPSIS was developed by (Hwang 1981), which is relatively an easy and fast MCE tool with systematic approach (Shanian and Savadogo 2006). In this method, the minimum distances to the positive ideal and maximum distance from the negative ideal plays an important role in ranking the alternative in geometric sense (Ertuğrul and Karakaşoğlu 2009). This technique is considered to be an easily comprehensible method which has a unique way of approach in solving multi criteria problems. Another main advantage of using this technique is that it does not limit the number of criteria identified in the decision-making process (Behzadian et al. 2012) .

Figure 3. 6 procedural steps involved in TOPSIS to assess and rank the alternative to meet the decision objective. Initially, the data-matrix is normalized to convert different units of various criteria into a common measurable unit. Then the weighted normalized decision

matrix is constructed using the weights of decision criteria and the normalized data-matrix. The most preferable (ideal positive) and least preferable (ideal negative) alternative is identified based on the weighted normalized decision matrix. Further, separation measure of alternative from most preferable and least preferable alternative is computed using Euclidean distance technique. Then the relative closeness of an alternative to the positive ideal solution is computed based on the separation measure. Finally, the ranking of alternatives is given according to the decreasing order of the relative closeness of an alternative to the positive ideal solution.



Normalizing the payoff matrix

$$r_{ij} = \frac{a_{ij}}{\sqrt{\Sigma {a^2}_{ij}}} \quad , \; j = 1, 2\ldots n;\; i = 1, 2\ldots.m$$

Where, r_{ij} element of normalized matrix R of alternative j under the evaluation criteria i.

a_{ij} element of decision matrix of alternative j under the evaluation criteria i.

Construction of the weighted normalized decision matrix v_{ij} by multiplying the normalized decision matrix r_{ij} with its associated weight (w_i).

Determination of the ideal positive A^* and ideal negative A^- solutions

$$A^* = \{v_1^* \ldots\ldots . v_m^*\} \quad , \; i = 1, 2.......m$$

$$A^- = \{v_1^- \ldots\ldots . v_m^-\} \quad , \; i = 1, 2.......m$$

Where, v_i^* = $\max_{ij}$ v_{ij} , v_i^- = $\min_{ij}$ v_{ij} , if i^{th} represents a maximization criteria.

v_i^* = $\min_{ij}$ v_{ij} , v_i^- = $\max_{ij}$ v_{ij} , if i^{th} represents a minimization criteria

Calculation of the separation measure of alternatives from ideal positive and ideal negative by Euclidean distance method

$$S_j^* = \sqrt{\sum_{i=1}^{n}(v_{ij} - v_i^*)^2} \qquad j = 1, 2, 3.......n$$

$$S_j^- = \sqrt{\sum_{i=1}^{n}(v_{ij} - v_i^-)^2} \qquad j = 1, 2, 3.......n$$

Where, s_j^*, s_j^- are the separation from the most and least preferable alternative.

The relative closeness of an alternative Aj to the ideal solution $A*$ is given by:

$$CC_j^* = \frac{S_j^-}{S_j^* + S_j^-} \qquad j = 1, 2, 3.......n$$

Figure 3. 6 TOPSIS methodology for assessing and ranking the alternatives (Shanian and Savadogo 2006)

TOPSIS has received over 13000 publications and has been widely used for practical MCE problems since its development (Salih et al. 2019; Behzadian et al. 2010; Subrata Chakraborty 2022). It is extensively used in a wide variety of applications ranging from health care, technology selection, product selection, material selection to education selection application. (Yong 2006) introduced a novel TOPSIS approach for choosing plant placements and evaluated the ranking of various locations for each criterion and the weights of multiple criteria using fuzzy linguistic concepts. Li et al. provided a framework that combines AHP and TOPSIS to assist designers in determining customer requirements and design features as well as in offering a final design solution for comparative benchmarking (Li et al. 2011). Aydogan explored by integrating AHP and fuzzy TOPSIS to analyse the performance of four aviation enterprises using five crucial dimensions viz. performance risk, quality, effectiveness, efficiency, and occupational satisfaction (Aydogan 2011). Sadeghzadeh & Salehi studied to identify potential strategies for the development of fuel cell technology in the automobile sector (Sadeghzadeh and Salehi 2011). Sadeghzadeh & Salehi developed a TOPSIS solution for a fuzzy multiple criteria group decision-making problem based on the preference ratio method in conjunction with an effective fuzzy distance measurement (Sadi-Nezhad and Damghani 2010). This wide range of applications is due to its strong mathematical foundation, simplicity, and ease of application and following are few reasons(Subrata Chakraborty 2022; Salih et al. 2019):

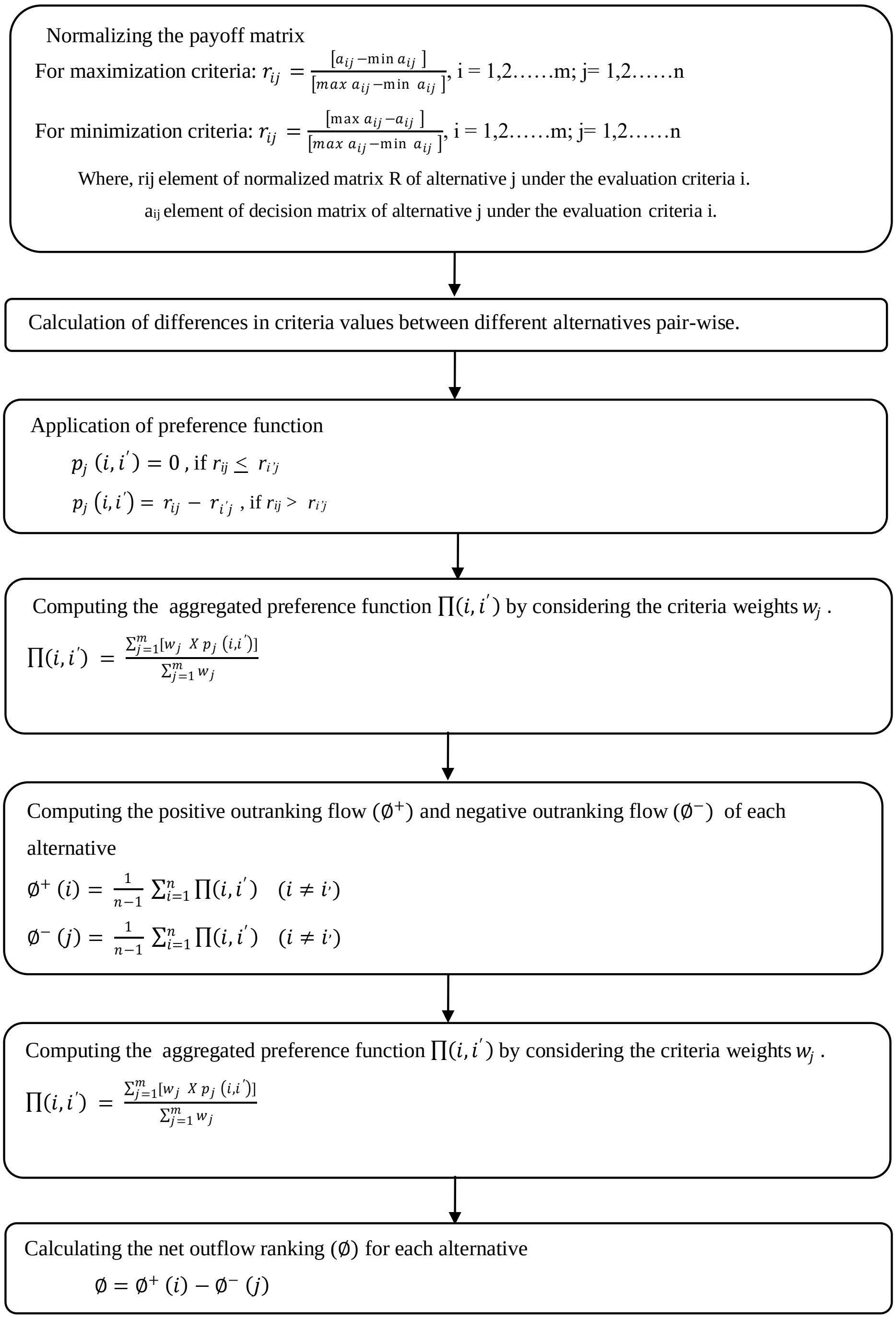
- It is a comparatively simple and fast MCE technique with a systematic approach.
- Easily understandable method in solving multi-criteria problems with a unique approach.
- It does not confine the size of evaluation criteria.
- Finds its successful application to MCE problems especially related to energy and sustainability.

3.3.2. Preference ranking organization method for enrichment evaluations II (PROMETHEE II)

The PROMETHEE method is one of the most widely used MCE techniques of outranking nature developed by Brans and Vincke and extended further by Brans, Vincke, and Mareschal (Brans and Vincke 1985; Brans and Mareschal 1986). The basic principle of PROMETHEE II is based on a pairwise comparison of alternatives with respect to each criterion and give the complete outranking of alternatives(Sennaroglu and Varlik Celebi 2018).

The stepwise procedure for ranking the alternative in PROMETHEE II is presented in *Figure 3.11*(Behzadian et al. 2010). Initially, the differences in criteria values between different alternatives is calculated pairwise by normalizing the payoff matrix. Further, the preference function is applied for each criterion to translate the difference between the evaluation obtained by two alternatives into a preference degree ranging from 0 to 1. In order to reduce the difficulty in selecting the suitable preference function from six basic types of preference functions for each criterion, a simplified preference function method proposed by Chakraborty & Athawale could be applied for a given problem (Chakraborty and Athawale 2010). Then the aggregated preference function is calculated by considering the criteria weights. The net out flow value is calculated by computing the positive outranking flow and negative outranking flow of each alternative. Finally, the alternative ranking is given according to the decreasing order of net out flow significance.

PROMETHEE II method finds its application in various fields such as environment management, hydrology and water management, chemistry, logistics and transportation, manufacturing and assembly, energy management, social, medicine, agriculture etc. by many researchers successfully to solve problems related to decision-making (Behzadian et al. 2010).



Normalizing the payoff matrix

For maximization criteria: $r_{ij} = \frac{[a_{ij} - \min a_{ij}]}{[max\ a_{ij} - \min\ a_{ij}]}$, i = 1,2……m; j= 1,2……n

For minimization criteria: $r_{ij} = \frac{[\max a_{ij} - a_{ij}]}{[max\ a_{ij} - \min\ a_{ij}]}$, i = 1,2……m; j= 1,2……n

Where, rij element of normalized matrix R of alternative j under the evaluation criteria i.

a_{ij} element of decision matrix of alternative j under the evaluation criteria i.

Calculation of differences in criteria values between different alternatives pair-wise.

Application of preference function

$p_j\ (i, i') = 0$, if $r_{ij} \leq r_{i'j}$

$p_j\ (i, i') = r_{ij} - r_{i'j}$, if $r_{ij} > r_{i'j}$

Computing the aggregated preference function $\prod(i, i')$ by considering the criteria weights w_j .

$$\prod(i, i') = \frac{\sum_{j=1}^{m}[w_j\ X\ p_j\ (i, i')]}{\sum_{j=1}^{m} w_j}$$

Computing the positive outranking flow ($\emptyset^+$) and negative outranking flow ($\emptyset^-$) of each alternative

$$\emptyset^+\ (i) = \frac{1}{n-1} \sum_{i=1}^{n} \prod(i, i') \quad (i \neq i')$$

$$\emptyset^-\ (j) = \frac{1}{n-1} \sum_{i=1}^{n} \prod(i, i') \quad (i \neq i')$$

Computing the aggregated preference function $\prod(i, i')$ by considering the criteria weights w_j .

$$\prod(i, i') = \frac{\sum_{j=1}^{m}[w_j\ X\ p_j\ (i, i')]}{\sum_{j=1}^{m} w_j}$$

Calculating the net outflow ranking ($\emptyset$) for each alternative

$$\emptyset = \emptyset^+\ (i) - \emptyset^-\ (j)$$

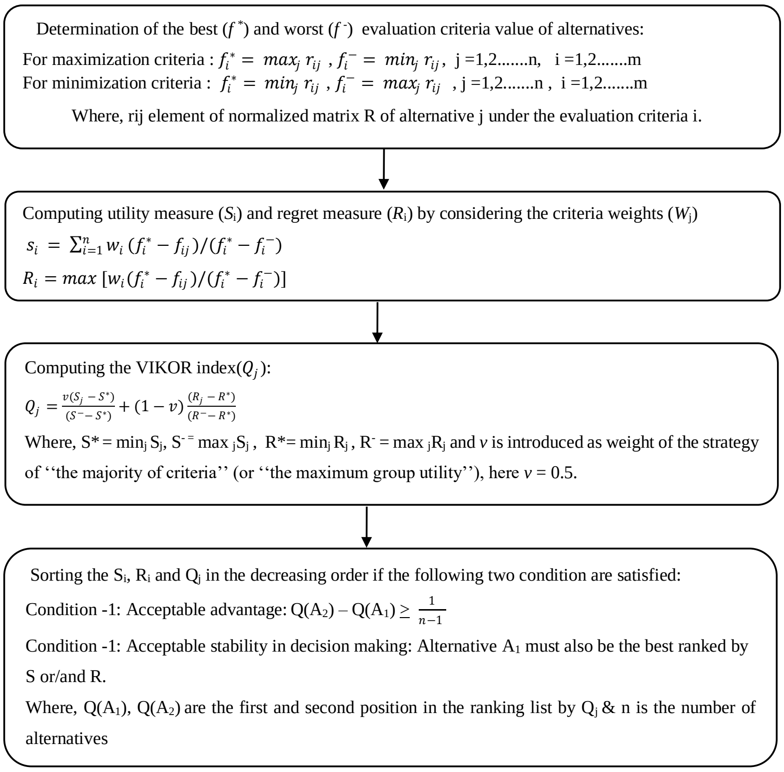
Figure 3.7 PROMETHEE II methodology for assessing and ranking the alternatives (Brans and Vincke 1985)

Using PROMETHEE I and II, D’avignon’ & Mareschal’ determined the specialised levels for hospital services provided in the Quebec region of Canada (D’avignon’ and Mareschal’ 1989). On the basis of 11 factors, the hospital services were ranked. Khelifi (2006) applied PROMETHEE II to evaluate and identify appropriate groundwater remediation technologies in terms of sustainability criteria viz. technical, economic, environmental, and social criteria (Khelifi 2006). In order to choose the best stocks for investing at the Tehran Stock Exchange (TSE), Albadvi et al., used PROMETHEE I and II as a decision-making tool (Albadvi, Chaharsooghi, and Esfahanipour 2006). In light of financial criteria, Baourakis et al. in 2002 applied PROMETHEE II to evaluate the viability of Greek enterprises in the production and commercialization of agricultural food products (Baourakis et al. 2002). Herngren et al., in 2006 applied PROMETHEE II, made up of eight heavy metal components, to evaluate residential, industrial, and commercial locations and five particle sizes as well as to assess the correlations between heavy metals and Total Organic Carbon (Herngren, Goonetilleke, and Ayoko 2006). One of the most extensively used MCE techniques for outranking

- Ranking is based on the pairwise comparison of alternatives with respect to each criterion
- Gives the complete and comprehensive alternatives ranking

3.3.3. Vlsekriterijumska optimizacija i kompromisno resenje (VIKOR)

The method VIKOR was developed by Opricovic in 1998 to solve decision problems with conflicting criteria (S Opricovic 1998). This method provides a list of compromise ranking based on a specific measure of closeness to the ideal solution (Serafim Opricovic and Tzeng 2004). The procedural steps involved in VIKOR for ranking the alternatives are illustrated in *Figure 3.8*. Initially, the data-matrix is normalized to convert different units of various criteria into a common measurable unit. The best and worst evaluation criteria value of alternative is determined from the normalized matrix. Further, the utility measure and regret measure by considering the criteria weights are computed which is followed by computation of VIKOR index and alternatives are sorted according to the increasing order of VIKOR index. The alternative with the smallest VIKOR value is determined to be the best value if only the condition 1 and 2 are satisfied. Otherwise, the maximum group utility is adjusted until two conditions mentioned in the VIKOR procedure are satisfied.



Determination of the best (f^*) and worst (f^-) evaluation criteria value of alternatives:

For maximization criteria : $f_i^* = max_j\, r_{ij}$, $f_i^- = min_j\, r_{ij}$, j =1,2.......n, i =1,2.......m

For minimization criteria : $f_i^* = min_j\, r_{ij}$, $f_i^- = max_j\, r_{ij}$, j =1,2.......n , i =1,2.......m

Where, rij element of normalized matrix R of alternative j under the evaluation criteria i.

Computing utility measure (S_i) and regret measure (R_i) by considering the criteria weights (W_j)

$s_i = \sum_{i=1}^{n} w_i\,(f_i^* - f_{ij})/(f_i^* - f_i^-)$

$R_i = max\,[w_i(f_i^* - f_{ij})/(f_i^* - f_i^-)]$

Computing the VIKOR index(Q_j):

$Q_j = \frac{v(S_j - S^*)}{(S^- - S^*)} + (1-v)\frac{(R_j - R^*)}{(R^- - R^*)}$

Where, $S^* = min_j\, S_j$, $S^- = max_j\, S_j$, $R^* = min_j\, R_j$, $R^- = max_j\, R_j$ and v is introduced as weight of the strategy of ‘‘the majority of criteria’’ (or ‘‘the maximum group utility’’), here $v = 0.5$.

Sorting the S_i, R_i and Q_j in the decreasing order if the following two condition are satisfied:

Condition -1: Acceptable advantage: $Q(A_2) - Q(A_1) \geq \frac{1}{n-1}$

Condition -1: Acceptable stability in decision making: Alternative A_1 must also be the best ranked by S or/and R.

Where, $Q(A_1)$, $Q(A_2)$ are the first and second position in the ranking list by Q_j & n is the number of alternatives

Figure 3.8 VIKOR methodology for assessing and ranking the alternatives (S Opricovic 1998)

Gul et al. comprehensively examined 343 journal publications that used VIKOR in various fields from 2000 to 2015 (Gul et al. 2016). It finds its application in various fields such as design and manufacturing management, environmental resources and energy management, education management business and marketing management, supply chain and logistics management, tourism management, etc.(Yazdani and Graeml 2014). Zhu et al. proposed a systematic evaluation that integrates AHP and VIKOR techniques to evaluate and assess design concepts in a subjective environment (Zhu et al. 2015). In order to prioritise land-use constraint methods in the watershed surrounding the Tseng-Wen reservoir, Chang & Hsu suggested a VIKOR-based MCE technique (Chang and Hsu 2011). According to the findings, land-use limitations should be prioritised for subdivisions that are adjacent to the outflow or reservoir area. Golić et al. suggested a VIKOR based approach for choosing the best solar water heating system (SWHS) to address the issue of SWHS integration through the renovation of residential structures in a suburban region of Belgrade (Golić, Kosorić, and Furundžić 2011). Furundzic et al. applied the VIKOR approach for comprehensive evaluation of design possibilities and selection of the best integrated solar thermal collector based on competing criteria viz. energy performance, economics, ecology, functionality, and aesthetics (Furundzic, Kosoric, and Golic 2012). Erdoğan Aktan & Kaya Samut applied fuzzy AHP and VIKOR to analyse the 2009 agricultural performance of Turkey's provinces using the agricultural performance criteria (Erdoğan Aktan and Kaya Samut 2013). Pourebrahim et al. used a hybrid VIKOR-fuzzy AHP technique to choose amongst potential conservation development options in a coastal area (Pourebrahim et al. 2014). Ju & Wang applied a traditional VIKOR approach and introduced a novel approach to handle multi-criteria group decision-making issues where both the criteria values and the criteria weights were expressed as linguistic data (Ju and Wang 2013). For this wide range of applications of VIKOR, many researchers have proposed the VIKOR to solve various decision problems.

3.3.4. Elimination et choix traduisant la realité I (ELECTRE I)

ELECTRE method was developed by Bernard Roy in 1991. This method appears in the models viz. ELECTRE I, II, III, IV, IS and TRI. Each model is based on the same background but operates in different ways (Figueira JR 2012). The method is characterized by thresholds and the outranking notion. This technique is considered to be simple with its wide applicability in a wide range of energy and sustainability problems (Roy B 1991). The procedural steps involved in ELECTRE I for ranking the alternatives are illustrated in *Figure 3.9*. To take up the further steps in the ranking process using ELECTRE I, the weighted normalized decision matrix is computed by considering the normalized matrix. Based on this weighted normalized data matrix and by considering the condition for concordance and discordance interval sets, the concordance and discordance matrix can be obtained. Further, the net superior value and the net inferior values are calculated. Finally, alternatives are ranked according to the decreasing order of net superior values and increasing order of the net inferior values.

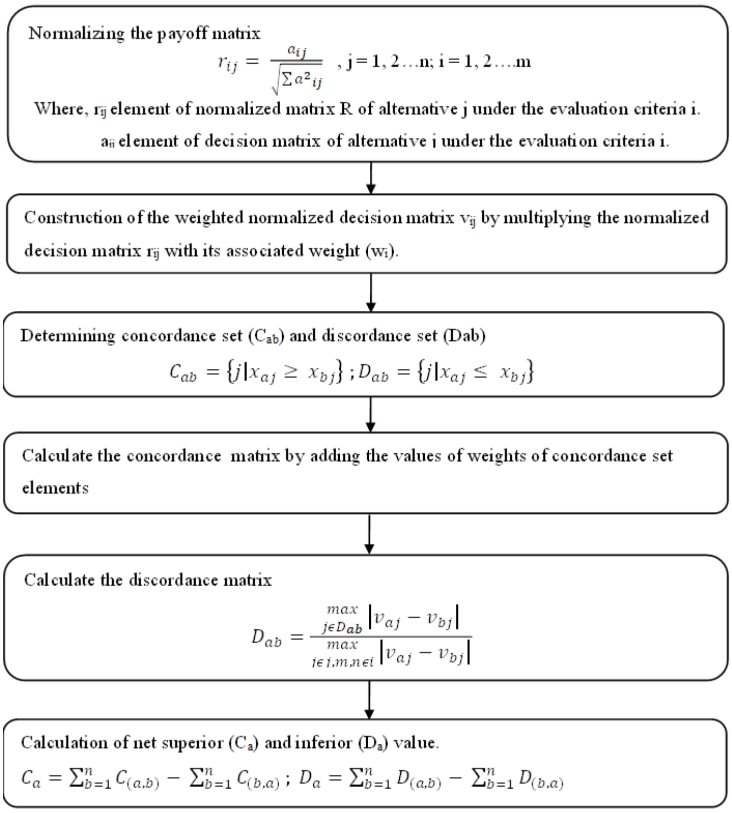


Figure 3.9 ELECTRE I methodology for assessing and ranking the alternatives (Figueira 2012)

ELECTRE I, despite being almost 40 years old, it is still used frequently in many different domains with 189 applications (Govindan and Jepsen 2016). This is possibly due to the fact that it requires less effort than the other approaches, making it simpler to incorporate into broader methodologies or to integrate with other MCE approaches. Applications for ELECTRE I increased until the early 1990s, after which there was a ten-year period of relative stagnation and has been increasing progressively from 2001(Govindan and Jepsen 2016). deAlmeida employed an ELECTRE I based decision model for outsourcing contracts selection, using informational uncertainty and utility functions as criterion (deAlmeida 2007). Amiri et al. explored using interval data in ELECTRE I and demonstrated the methodology for evaluating 15 bank branches in Iran (Amiri 2008). Gurmeric et al. applied ELECTRE I along with three additional MCE techniques to determine the perfect flavour for prebiotic pudding, according to sensory assessments for each of the three flavours viz. strawberry, vanilla, and cacao (Gurmeric 2012).

3.4. MCE - a possible tool to fill the research gaps

As presented in the previous chapter, NCS industry is one of the oldest small-scale cottage industries in India, operated and manned by local farmers with crude and inferior production techniques that are unchanged for several decades. These crude, unchanged, energy inefficient, technologically inferior production techniques resulted in continued downfall of the NCS Industry in India over the last few decades despite nutritional, medicinal and other favourable features of NCS. In order to revive this once very well-established rural cottage industry, it becomes essential to investigate all the reasons for this declining trend. The first step to address this is to focus on assessing how the existing NCS production technologies and the alternatives for the same could contribute for the sustenance of the NCS Industry. This could be done by analysing different alternatives for different sub-processes with respect to different criteria related to techno-economics, resource utilization, environmental impacts and process output parameters. Such an analysis would suggest a better alternative for the NCS production process line. Summarising the contents presented in the previous chapter and present chapter, the following, in sequence, could be arrived at:

- The production of NCS involves four important and basic sub-processes viz. juice extraction, juice clarification, juice evaporation, NCS drying.
- The sustenance of the NCS industry is dependent on the sustenance of these individual sub-processes.
- It is not clearly known if the current technologies or their alternatives for each of these processes would serve their intended purpose.
- Analysis of these alternatives is governed by multiple criteria related to techno-

economics, resource utilization, environmental impacts and process output parameters.

- With its quite well-established philosophy of evaluation, MCE is a powerful tool to bring out solutions for the problems involving multiple criteria as successfully demonstrated in several fields of studies.

Based on all these, it could be hypothesized that the MCE could be used as a tool to bring out solutions for the sustenance of the NCS industry.

3.5. Thesis objectives

Based on the above-mentioned hypothesis, the overall objective of the thesis is

- To bring out MCE based solutions for the sustenance of the NCS industry w.r.t. techno-economics, resource utilization, environmental impacts and process output parameters.

The inherent sub-objectives are:

- To prioritize the juice extraction and clarification technologies using MCE and suggest a better one among these for the sustenance of NCS industry.
- To prioritize the juice evaporation technologies using MCE and suggest a better one among these for the sustenance of NCS industry.
- To prioritize the NCS drying technologies using MCE and suggest a better one among these for the sustenance of NCS industry.

3.6. Scope of the research work

As identified through literature and field studies, for its sustenance, the NCS industry requires simultaneous addressing of many techno-economic-commercial and allied barriers. However, this thesis mainly focuses on using MCE tools to bring out the best among the existing technologies for different sub-processes of NCS production, as a way to address some of these barriers. These MCE tools use identified techno-economic, resource utilization, environmental impact and process output parameters.

4. MCE of Technologies for Juice Extraction and Clarification Sub-Processes

Keywords

Juice extraction

Juice clarification

Multi-criteria evaluation

Crushing technology

Organic clarificants

Plant mucilage

In the production of NCS, juice extraction and juice clarification are the primary and essential processes. The quantity of NCS produced per batch is defined by the type of juice extraction process employed, while the quality of NCS is defined by the type of clarification process adopted. Both physical and chemical impurities present in the juice are removed through the clarification sub-process. For both of these sub-processes, a wide variety of technologies are in practice although it is not very clear which of these are more sustainable and suitable for producing quality NCS. As presented in the subsequent sections of this chapter, finding sustainable and suitable technologies among the many technologies available for these processes, is governed by multiple criteria. This chapter presents the undertaken MCE based works to find a suitable and sustainable juice extraction technique and clarification method.

4.1. MCE of juice extraction process

Juice extraction, which is achieved by crushing the sugar cane in a crusher, is the primary and critical sub-process in the production of NCS. The main objective of this sub-process is to extract the maximum amount of juice present in the sugarcane, which mainly depends on the type of juice extraction technique adopted. Generally, in conventional NCS production units, it is customary to use power operated crushers (diesel engine or electric motor as prime movers) with vertical or horizontal rollers, not bothering much about the crushing efficiencies, the quantity of juice obtained or the quantity of juice left out in bagasse. The juice left out in the bagasse brings down (a) the amount of juice available for NCS production (b) the calorific value of the bagasse and thus overall plant efficiency (c) quality, and quantity of the NCS produced. Thus, inappropriate, inefficient, crushing methods adopted contribute to the financial burden to the stakeholders in the supply chain, market failure and ultimately the decline of the NCS industry as a whole. Field surveys undertaken and the reported literature indicate that the typical values of extraction efficiencies of such conventional crushers vary from 50 to 55% (for vertical crushers) and 55 to 60% (for horizontal crushers)(P. Jagannadha Rao, Das, and Das 2007). Apart from the above two technologies, wide varieties of juice extraction technologies are available in the regular sugar engineering practice as well as in the literature. Some of these are, crushers with shredders; crushers with multiple mills; crushers that facilitate hot water usage (to increase the quantity of juice) and so forth (Lobo et al. 2007). However, each juice extraction technique has some distinguishing feature from another. For example, some methods have more crushing efficiencies, some require more power, some have more water usage for crushing to obtain more yield, some have higher initial investments, some require less crushing time, some methods are only suitable for large scale application, some require a smaller number of man-hours for operation and so on. All the above implies, choosing the right juice extraction technology is a complex problem governed by several mutually conflicting sustainability criteria, thereby qualifying it to be solved by MCE.

In the work presented here, the necessary MCE computations were carried out by considering 11 criteria covering three main sustainability criteria namely, (a) resources & environmental effects (b) techno economic, and (c) process output parameters, to identify suitable and sustainable crushing technology among 6 crushing technologies. *Figure 4.1* presents the methodology adopted for this.

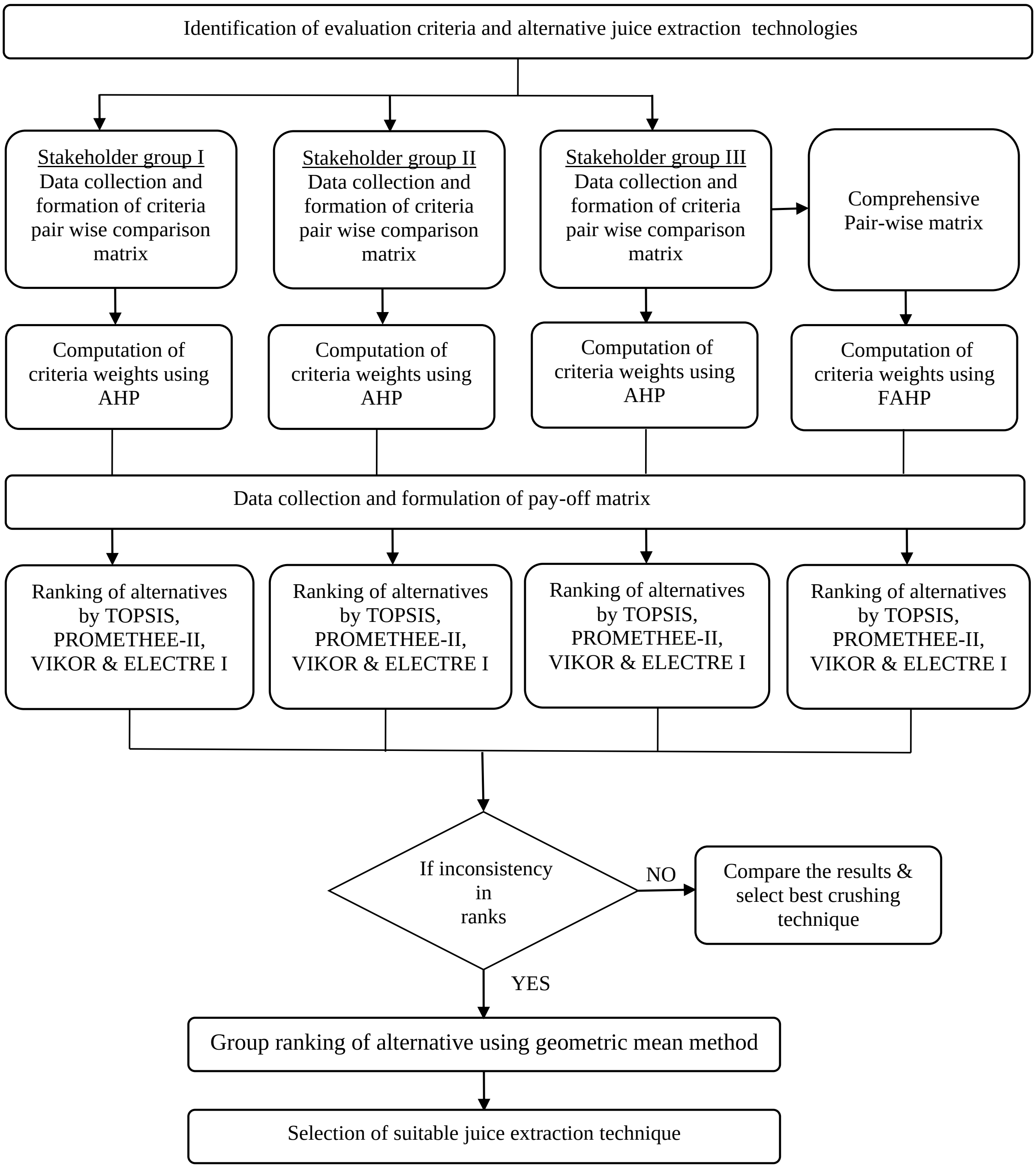


Figure 4.1 Methodology adopted for the selection of sustainable juice extraction technique

For the present MCE of identifying the sustainable juice extraction technique, three stakeholder groups are considered viz. (i) academics and sustainability promoters (15 numbers), (ii) NCS manufactures (10 numbers) and (iii) NCS plant suppliers (3 numbers). The inputs from stakeholders are obtained through personal interviews, questionnaire-based surveys during field studies at Anakapally, AP, India (the well-established market for NCS for the last several decades) during March 6 to 12, 2019. Individual stakeholder groups inputs were considered for computing the criteria weights using AHP & FAHP. Further, alternative juice extraction technologies are assessed by MCE techniques viz. TOPSIS, PROMETHEE II, VIKOR & ELECTRE I. The following sections describe the methodology adopted for identifying the sustainable juice extraction technique for NCS industry.

4.1.1 Identification of evaluation criteria

To identify the applicable criteria, initially, a thorough literature survey was conducted, based on which a set of questionnaires (that aid in obtaining the information from field survey) were prepared. This was followed by a field survey at Anakapally, a locality in south India, prominent for several NCS cottage industries and a very well established NCS market for the last several decades. Through these, a comprehensive list of more than 25 criteria covering the above-described sustainability aspects was made. As per the standard MCE theory, the criteria selected must be mutually exclusive, nonredundant, absolute, should be in minimum number and manageable (Kaya and Kahraman 2010). Through several brainstorming sessions with the considered stakeholder groups (March 20 to 25, 2019) some of the criteria were clubbed, some of the criteria were divided into two or more criteria. For instance, criteria namely, “direct emissions" and “indirect emissions” were clubbed together as “emissions.” Similarly, criteria viz. “total production cost” was divided into “energy cost,” “capital cost,” and “maintenance cost.” These systematic processes resulted into a final set of 11 criteria distributed among the techno-economic, resource utilization, environmental impact and process output parameters. Definitions of these 11 criteria, along with their nature that is, maximization or minimization, as suitable for selecting the best juice extraction technique for the sustenance of NCS industry, are as given in Table 4.1.

Table 4.1 Definition of the criteria, their nature and units

Main criteria	Sub Criteria		Definition	Units	Max/ Min
Resources & environmental effects	C_1	Water	The amount of water required in a crushing process to get the desired sugarcane juice.	Liters	Min.
	C_2	Energy	The total amount of energy required to crush one tonne of sugarcane to get the desired sugarcane juice	kWhr.	Min.
	C_3	Man-hours	The time taken by total number of workers to carry out the crushing process for one tonne of cane.	Hours	Min.
	C_4	Emissions	The direct or indirect emissions emerged out due to the consumption of energy source	CO_2 equivalent / kWhr.	Min.
Techno-economic	C_5	Energy cost	The cost incurred on the energy spent to complete the crushing process for one tonne of cane.	₹	Min.
	C_6	Capital cost	The cost incurred on crushers and other accessories to extract maximum amount of juice from one tonne of cane.	₹.	Min.
	C_7	Process time	Time taken to convert one tonne of sugarcane into sugarcane juice.	Hours	Min.
	C_8	Maintenance cost	The cost incurred to keep the crushers and other accessories in good working conditions for one tonne of cane.	₹.	Min.
	C_9	Level of automation (LOA)	The degree to which the crushing process is automated which is rated on a scale of 1-5	-	Max.
Process output parameters	C_{10}	Quantity of juice	The amount of juice extracted from one tonne of sugarcane through the crushing process.	Liters	Max.
	C_{11}	Brix	The concentration of cane juice for one tonne of cane	Degrees (^{o}brix)	Max.

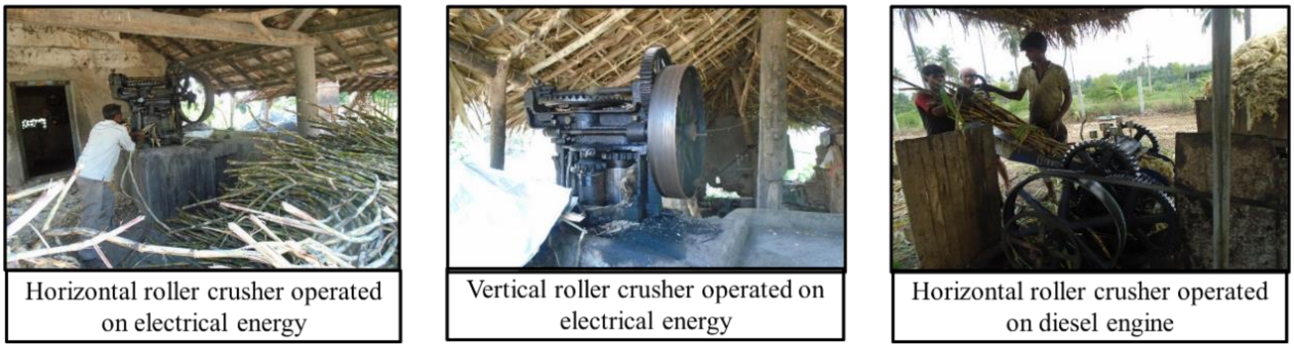
4.1.2 Alternative technologies for juice extraction

After thorough literary investigations and field studies on the juice extraction practices being followed in the NCS production as well as in sugar industries. Initially, a list of nine different juice extraction techniques was identified. Among these nine alternatives, six are current practices identified from the literature works and from onsite field survey. The additional three alternatives were identified with an idea of replacing conventional energy sources with the energy from solar photovoltaic (SPV) to run the crushing process. However, the preliminary techno-economic analyses of these SPV based systems turned out to be inferior options in view of the possible mismatch between the load vs supply characteristics and associated economics of power generation and its use. As observed from field and literature surveys, the existing juice extraction techniques differ with each other in terms of the type and number of rollers used, primary energy resource for running the crusher, usage of hot water to increase the yield of juice, and usage of any other additional attachments to increase the juice recovery. The field and literature surveys indicate that there are five extensively used techniques whose details are as indicated in *Table 4.2*. On-sight pictures of three juice extraction techniques obtained during field studies carried out at various NCS plants in Anakapalle, Andhra Pradesh, India, areas are shown in *Figure 4.2*. Also, use of shredders that cut the sugar cane into small segments, which are then crushed in a horizontal crusher to get the required juice is a regular practice used in conventional sugar industry. To explore the utility of this in NCS manufacturing, this option was also considered as an alternative.

In single vertical (SVEN) and horizontal crushers (SHEN) that are operated on electrical power, the three rollers are arranged vertically and horizontally, respectively, in the form of a triangular tandem operated by means of electric power. These two alternatives require comparatively less energy and capital cost and also relatively less extraction efficiency ranges about 50% and 55–60%, respectively. The alternative SHDN is similar to alternative SHEN in roller arrangement, but operated by means of diesel and the extraction efficiency ranges ~50–55% [5]. Similarly, for alternative MHEN, multiple horizontal mills (two or three mills) are arranged in series each with three fluted rollers operated by means of electrical power and whose extraction efficiency ranges between 65% and 70% [6]. Alternative MHEY, widely used in the sugar industry is more similar to the alternative MHEN; however, the juice extraction is done with the addition of hot water, whose extraction efficiency ranges between 75% and 80%. All these techniques of juice extraction vary with each other according to the usage of type and number rollers, the primary source of energy used to operate the crusher and the use of hot water to increase juice recovery.

Table 4.2 Alternative juice extraction techniques

Crushing alternative	**Type of roller**	**Number of rollers**	**Primary energy source to run the crusher**	**Hot water usage**	**Additional attachments**
SVEN	Vertical	Single	Electrical energy	NO	-
SHEN	Horizontal	Single	Electrical energy	NO	-
SHDN	Horizontal	Single	Diesel	NO	-
MHEN	Horizontal	Multiple	Electrical energy	NO	-
MHEY	Horizontal	Multiple	Electrical energy	YES	-
ShSHEN	Horizontal	Single	Electrical energy	NO	Shredder



Horizontal roller crusher operated on electrical energy

Vertical roller crusher operated on electrical energy

Horizontal roller crusher operated on diesel engine

Figure 4.2 Current practice of juice extraction techniques observed during field studies

4.1.3 Computation of evaluation criteria weights

The decision hierarchy for the present problem of selecting a suitable juice extraction technique for NCS production in the MCE environment is presented in *Figure 4.3.* Of all the methods for criteria weights computations, AHP and FAHP methods are adopted for this for the following reasons (Kubler et al. 2016; Emrouznejad and Marra 2017): Analytic hierarchy process (AHP) has received a lot of attention due to its simplicity, use, and high degree of adaptability. It is employed in almost all applications involving MCE since it is developed. The second-best weight estimation method is the FAHP and is widely used whenever there is a fuzziness involved in the data given by stakeholder groups.

In the present decision problem, one of the criteria is rated on its qualitative terms and the decision given for this particular criterion is based on qualitative rating. Therefore, to avoid fuzziness given by different stakeholder groups with respect to qualitative criterion and also, to know their individual decision on the final outcome, both the weight estimation methods are considered. The methodology adopted for these two methods is as presented in *Figure 3.3* & *Figure 3.4*. The computation of criteria weights using AHP & FAHP is based on the pairwise comparisons between two criteria by using Saaty's nine-point scale of relative importance (Saaty and Katz 1990). For the present decision problem, format of questionnaires presented in Appendix I were used to elicit the required data from each stakeholder group. This information has been obtained from the above mentioned three stakeholder groups through personal interactions during field studies conducted on 6–12March 2019 at a study area viz. Anakapally, Andhra Pradesh, India. Pairwise comparisons of each criterion as given by three stakeholder groups are as presented in *Table 4.3, Table 4.4 & Table 4.5.*

Table 4.3 Pairwise comparison matrix – Stakeholder group I

Sub criteria	C_1	C_2	C_3	C_4	C_5	C_6	C_7	C_8	C_9	C_{10}	C_{11}
C_1	1	0.143	0.2	0.143	0.143	0.143	0.333	3	0.2	0.2	0.333
C_2	7	1	3	2	0.333	0.333	5	9	3	3	5
C_3	5	0.333	1	3	0.25	0.2	3	7	3	2	5
C_4	7	0.5	0.333	1	0.333	0.333	5	8	5	3	5
C_5	7	3	4	3	1	0.333	5	9	5	5	6
C_6	7	3	5	3	3	1	7	9	6	5	6
C_7	3	0.2	0.333	0.2	0.2	0.143	1	6	2	0.333	2
C_8	0	0.111	0.143	0.125	0.111	0.111	0.167	1	0.2	0.167	0.2
C_9	5	0.333	0.333	0.2	0.2	0.167	0.5	5	1	0.333	3
C_{10}	5	0.333	0.5	0.333	0.2	0.2	3	6	3	1	3
C_{11}	3	0.2	0.2	0.2	0.167	0.167	0.5	5	0.2	0.333	1

Table 4.4 Pairwise comparison matrix – Stakeholder group II

Sub criteria	C1	C2	C3	C4	C5	C6	C7	C8	C9	C10	C11
C_1	1	0.143	0.143	3	0.125	0.143	0.2	0.25	0.5	0.143	0.2
C_2	7	1	0.5	7	1	0.333	3	2	7	1	1
C_3	7	2	1	8	1	0.333	2	2	7	0.5	0.5
C_4	8	1	1	8	1	0.333	2	2	7	1	1
C_5	5	0.333	0.5	5	1	0.333	1	1	5	0.5	0.5
C_6	7	3	3	5	3	1	3	4	5	4	4
C_7	4	1	0.5	5	1	0.25	2	1	5	0.5	0.5
C_8	2	0.143	0.143	4	0.143	0.2	0.2	0.2	1	0.2	0.2
C_9	3	0.143	0.125	1	0.125	0.2	0.2	0.2	0.25	0.143	0.143
C_{10}	7	1	2	7	1	0.25	2	2	5	1	1
C_{11}	6	1	2	7	1	0.25	2	2	5	1	1

Table 4.5 Pairwise comparison matrix – Stakeholder group III

Sub criteria	C_1	C_2	C_3	C_4	C_5	C_6	C_7	C_8	C_9	C_{10}	C_{11}
C_1	1	0.2	0.333	2	0.2	0.143	0.167	0.333	0.143	0.143	0.5
C_2	5	1	2	5	2	0.2	0.333	3	0.2	0.143	5
C_3	3	0.5	1	5	3	0.2	0.333	2	0.333	0.25	4
C_4	0.5	0.2	0.2	1	0.333	0.111	0.2	0.333	0.111	0.143	0.333
C_5	5	0.5	0.333	3	1	0.143	0.25	2	0.25	0.2	3
C_6	7	5	5	9	7	1	3	7	3	4	7
C_7	6	3	3	5	4	0.333	1	7	0.25	0.333	5
C_8	3	0.333	0.5	3	0.5	0.143	0.143	1	0.2	0.2	2
C_9	7	5	3	9	4	0.333	4	5	1	2	7
C_{10}	7	7	4	7	5	0.25	3	5	0.5	1	7
C_{11}	2	0.2	0.25	3	0.333	0.143	0.2	0.5	0.143	0.143	1

Table 4.6 Comprehensive pair-wise comparison matrix

	C1	C2	C3	C4	C5	C6	C7	C8	C9	C10	C11
C1	(1,1,1)	(0.17,0.21,0.28)	(0.19,0.24,0.31)	(0.63,0.95,1.26)	(0.15,0.18,0.22)	(0.13,0.14,0.17)	(0.21,0.26,0.37)	(0.5,0.7,1)	(0.17,0.21,0.28)	(0.14,0.16,0.2)	(0.24,0.32,0.5)
C2	(3.63,4.72,5.77)	(1,1,1)	(0.69,1.06,1.44)	(0.63,0.95,1.26)	(0.4,0.61,0.91)	(0.17,0.21,0.26)	(0.55,0.69,0.91)	(1.82,2.38,3.3)	(0.87,1.22,1.59)	(0.35,0.44,0.55)	(1.39,1.71,2.08)
C3	(3.17,4.22,5.24)	(0.69,0.94,1.44)	(1,1,1)	(3.63,4.72,5.77)	(1.72,1.55,2)	(0.19,0.24,0.31)	(1,1.44,2)	(2.88,4.12,5.24)	(1.26,1.71,2.29)	(0.41,0.63,1)	(1.44,1.88,2.47)
C4	(0.63,1.05,1.59)	(0.173,0.21,0.26)	(0.17,0.21,0.28)	(1,1,1)	(0.22,0.28,0.4)	(0.15,0.17,0.2)	(0.44,0.52,0.63)	(0.66,0.81,1.04)	(0.48,0.57,0.69)	(0.3,0.36,0.42)	(0.5,0.62,0.79)
C5	(4.58,5.6,6.6)	(1.1,1.65,2.52)	(0.5,0.64,0.85)	(2.52,3.56,4.58)	(1,1,1)	(0.16,0.19,0.24)	(0.58,0.75,1)	(2.08,3.3,4.33)	(1.47,1.84,2.29)	(0.48,0.58,0.72)	(1.26,1.65,2.11)
C6	(6,7,8)	(3.63,4.72,5.77)	(3.17,4.22,5.24)	(5.01,6,6.87)	(4.16,5.28,6.35)	(1,1,1)	(3.3,4.38,5.43)	(6,6.8,7.56)	(3.91,5.01,6.07)	(2.29,3.42,4.48)	(3.91,5.01,6.07)
C7	(2.71,3.78,4.82)	(1.39,1.44,2.88)	(0.5,0.69,1)	(1.59,1.91,2.29)	(1,1.34,1.71)	(0.18,0.23,0.3)	(1,1,1)	(3.91,5.01,6.07)	(0.93,1.36,1.82)	(0.21,0.28,0.4)	(1,1.49,2.08)
C8	(1,1.44,2)	(0.3,0.42,0.55)	(0.19,0.24,0.35)	(0.96,1.23,1.51)	(0.23,0.3,0.48)	(0.13,0.15,0.17)	(0.16,0.2,0.26)	(1,1,1)	(0.38,0.49,0.63)	(0.16,0.19,0.23)	(0.30,0.43,0.57)
C9	(3.63,4.72,5.77)	(0.63,0.82,1.14)	(0.44,0.58,0.79)	(0.44,0.58,0.79)	(0.44,0.54,0.68)	(0.16,0.2,0.26)	(0.55,0.74,1.08)	(1.59,2.03,2.62)	(1,1,1)	(0.35,0.51,0.72)	(1.25,1.61,2)
C10	(5.24,6.26,7.72)	(1.82,2.27,2.89)	(1,1.59,2.47)	(1,1.59,2.47)	(1.39,1.71,2.08)	(0.22,0.29,0.44)	(2.52,3.56,4.58)	(4.331,5.31,6.32)	(1.39,1.96,2.88)	(1,1,1)	(2.29,3.48,4.58)
C11	(2,3.11,4.16)	(0.48,0.58,0.72)	(0.41,0.53,0.69)	(0.41,0.53,0.69)	(0.48,0.61,0.79)	(0.16,0.2,0.26)	(0.48,0.67,1)	(1.75,2.32,3.3)	(0.44,0.52,0.63)	(0.22,0.29,0.44)	(1,1,1)

As per the set procedure AHP (*Figure 3.3*), the criteria weights are computed for individual comparison matrices of stakeholders and their level of consistency is tested by means of consistency ratio (CR). In the event of inconsistency, the decision-maker in three considered stakeholder groups were directed to revise the elements of matrix to arrive at better consistency and for which the criteria weights are recalculated.

Further, for the weight computation by FAHP (*Figure 3.4*), the pairwise comparison matrix from the three stakeholder groups was fuzzified using triangular fuzzy membership functions. Then, the geometric mean method of Buckley is used to build a comprehensive pairwise comparison matrix and to compute the criteria weights. The comprehensive pairwise comparison of the 11 criteria with respect to the overall objective by three decision makers is aggregate in

Table 4.5. Based on this aggregated pairwise comparison matrix, the criteria weights were then computed

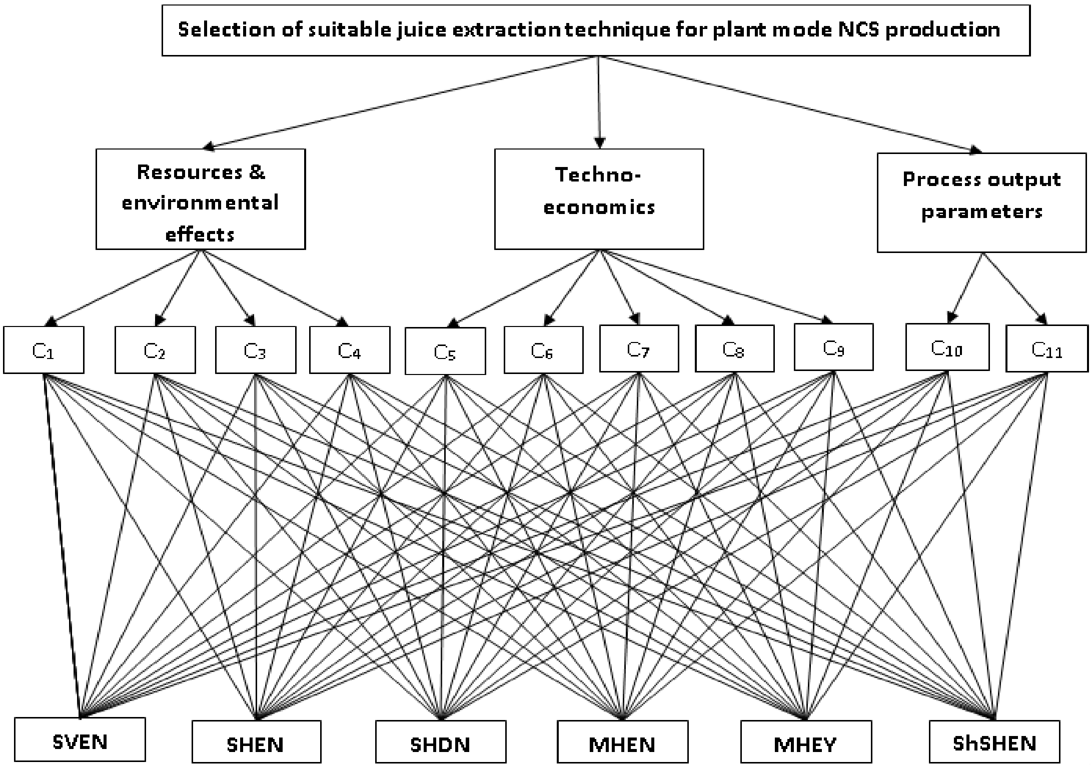


Figure 4.3 Decision hierarchy for juice extraction technique for NCS production

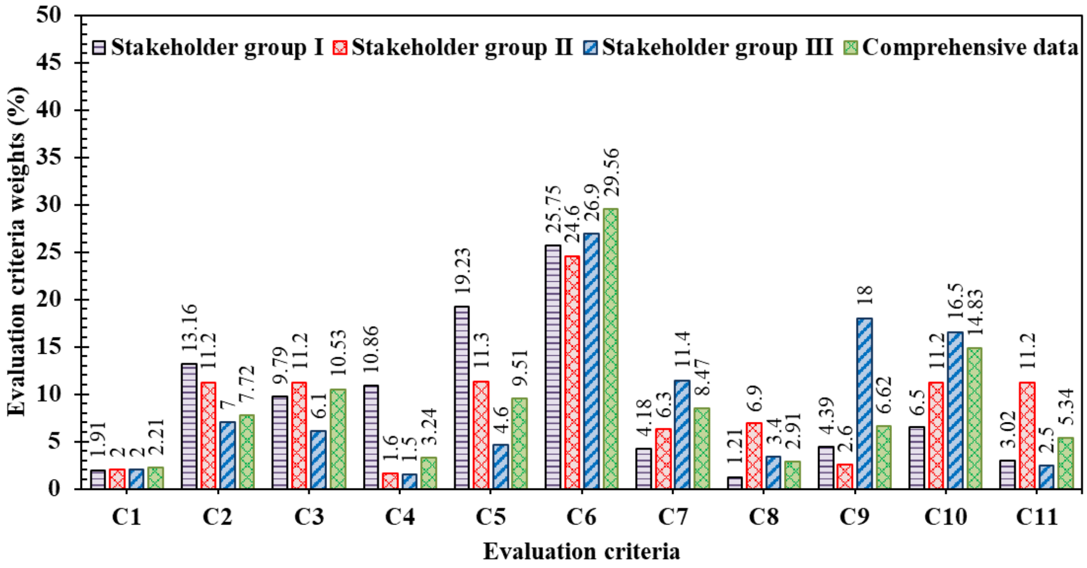


Figure 4.4 Evaluation criteria weights to assess the appropriate juice extraction technology

Figure 4.4 illustrates the AHP & FAHP weights of 11 evaluation criteria for selecting a suitable and sustainable crushing technology for NCS production w.r.t. three stakeholder groups & comprehensive data. Among all 11 evaluation criteria, capital cost (i.e., the cost of machinery) was found to be the most important criteria with respect to all three stakeholder groups & comprehensive data. Individually, for stakeholder I, sustainability factors such as energy required, energy cost and emissions are found to be more important criteria. Similarly, for stakeholder II, quantity and quality of NCS production with effective man-hours are emerged out to be the most important criteria. Likewise, for stakeholder group III, production rate was emerged out to be more important criteria such that the crushers designed for NCS production must be automated and be made less labor-intensive. For comprehensive data, amount of juice extracted, working hours & energy costs takes the next best weightage. Further, CR with respect to the preference of stakeholder groups I, II, III & comprehensive data are found to be 0.088, 0.0593, 0.078 & 0.075 respectively. Since the CR is ≤0.1, the computed weights are considered for further assessing of alternative juice extraction technologies.

4.1.4 Data formulation

The method of ranking the alternatives using any MCE technique starts with formulating a payoff matrix that contains the performance of alternatives with respect to the identified criteria along with the criteria weights (as computed using AHP technique in the present case). The required data on performance of three alternatives, (i.e., SVEN, SHEN, and SHDN), with respect to 11 evaluation criteria was elicited through field study conducted at Anakapally, a locality in south India, prominent for several NCS cottage industries. This study was conducted during March 6 to 12, 2019. Similar information for the alternative ShSHEN was obtained through field study at an upcoming NCS plant conducted at Erode, Tamil Nadu, India during October 7 to 10, 2018. For the remaining two alternatives namely, MHEN and MHEY, the data were obtained through literature sources(Pellegrini and de Oliveira Junior 2011; Lobo et al. 2007; Dutta D 2015). The data so obtained for all above-mentioned alternatives was compared with the similar data available in the literature sources. *Table 4.7* provides this consolidated data matrix (Pay-off matrix) for crushing one tonne of sugarcane along with the literature sources. The data for each criterion given in *Table 4.7* is self-explanatory when looked in conjunction with the definitions of the criteria given in *Table 4.1*.

4.1.5 Assessment & selection of alternative technology for juice extraction

The required computations to assess & select a suitable juice extraction technique for NCS production were undertaken by using four MCE techniques namely, TOPSIS, PROMETHEE II, VIKOR & ELECTRE I. The reason for considering these methods is because of its successful application to MCE problems especially related to energy and sustainability that covers both categories of MCE i.e., multi-attribute utility theory (MAUT) and outranking methods(Sotoudeh-Anvari 2022; Stojčić et al. 2019). The assessment by these MCE techniques require data formulated in the pay-off matrix and the evaluation criteria weights obtained by two MCE weight estimation methods viz. AHP & FAHP.

Table 4.7 Pay-off matrix for juice extraction technologies

Alternatives	Sub criteria											Reference
	C_1	C_2	C_3	C_4	C_5	C_6	C_7	C_8	C_9	C_{10}	C_{11}	
SVEN	0*	8*	4*	11.38	37[a]	155000*	90*	163*	1*	540*	20*	(P. Jagannadha Rao, Das, and Das 2007; Ramarao 2011; Malkunje et al. 2017; Velásquez et al. 2019),
SHEN	0*	5*	2*	7.11	32[a]	150000*	40*	155*	2*	545*	20*	(Rakesh Kumar and Kumar 2018; Ramarao 2011; Malkunje et al. 2017; Dutta D 2015; Velásquez et al. 2019)
SHDN	0*	4*	2*	5.67	230[a]	160000*	40*	174.8*	2*	537.5*	20*	(Rakesh Kumar and Kumar 2018; Ramarao 2011; Malkunje et al. 2017; Velásquez et al. 2019)
MHEN	0*	15*	2.5*	21.34	90[a]	450000*	45*	224.4*	3*	650*	20*	(Velásquez et al. 2019; Ramarao 2011; Malkunje et al. 2017)
MHEY	300*	15*	0.6*	21.34	90[a]	1000000*	35*	150*	5*	750*	15*	(Lobo et al. 2007; Velásquez et al. 2019)
ShSHEN	0*	8*	2.5*	11.38	37[a]	4500000*	32*	250*	4*	570*	20*	-

*Obtained from field studies [a] Estimated based on present electricity/fuel cost.

As per the TOPSIS assessment methodology, initially, the normalized payoff matrix was constructed. Then the weighted normalized matrixes were calculated. Based on this weighted normalized matrix the relative closeness to the ideal solution value of alternatives was calculated. *Table 4.8* presents the relative closeness to the ideal solution value of alternatives with respect to three stakeholder groups. Further, the alternative juice extraction technologies are ranked according to the decreasing order of this relative closeness to the ideal solution value. *Figure 4.5* presents the alternative ranking for the preferences of three stakeholders using the TOPSIS approach.

Table 4.8 Assessment values of alternative juice extraction technologies in TOPSIS

Alternatives	Stakeholder I	Stakeholder II	Stakeholder III	Comprehensive Data
	CC_j^*	CC_j^*	CC_j^*	$CCj*$
SVEN	0.804	0.768	0.688	0.444
SHEN	0.905	0.887	0.776	0.843
SHDN	0.639	0.728	0.758	0.671
MHEN	0.726	0.765	0.790	0.665
MHEY	0.694	0.734	0.789	0.699
ShSHEN	0.381	0.298	0.281	0.650

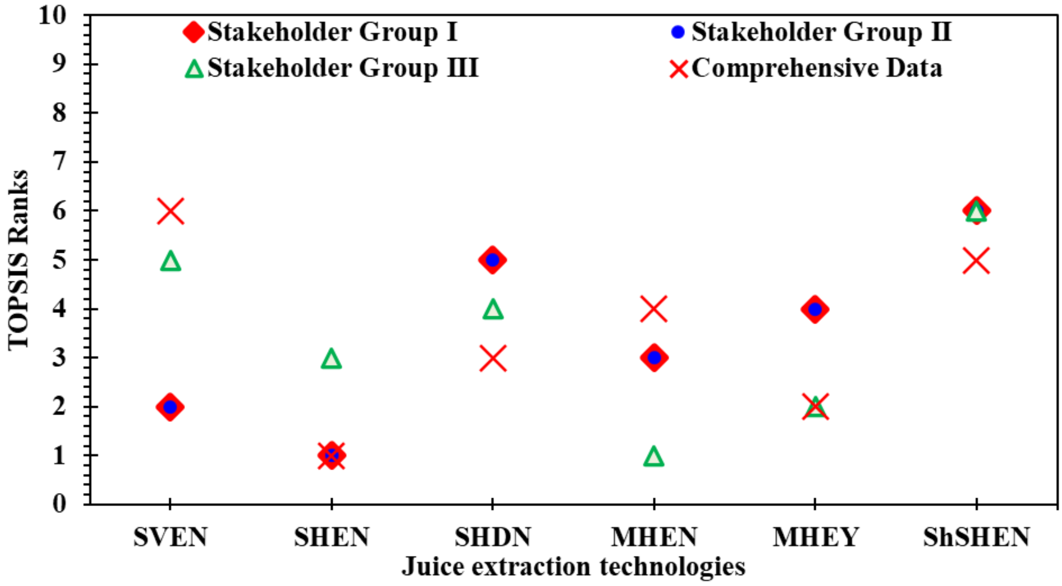


Figure 4.5 Ranking of alternative juice extraction technologies in TOPSIS

It is observed from *Figure 4.5* that the alternative SHEN was best ranked with respect to stakeholder groups I and II. Similarly, according to stakeholder III preferences, the alternative MHEN was ranked best. In addition, it could be observed that alternative ShSHEN which is the current practice at one of the NCS manufacturing plant at Erode was the least preferred method for the sustenance of the NCS industry with respect to all three stakeholder preferences. The current practice of using alternatives SVEN and SHDN are also comparatively least ranked with regard to all three stakeholders for NCS production. Also, from comprehensive data, SHDN & MHEY were observed be the best rank alternative juice extraction technology for NCS production.

According to PROMETHEE II methodology, Initially, the normalized pay off matrix was constructed. Then the aggregated preference function was computed. Further, the net outflow ranking of each alternative was computed by calculating the positive outflow and negative outflow of each alternative juice extraction technology. *Table 4.9* presents the net outflow ranking of each alternative. Finally, the alternative juice extraction technologies are sorted according the decreasing order of this net outflow ranking value of each alternative. *Figure 4.6* presents the alternative ranking with respect to priorities of individual stakeholders in PROMETHEE II.

Table 4.9 Assessment values of alternative juice extraction technologies in PROMETHEE II

Alternatives	Stakeholder I	Stakeholder II	Stakeholder III	Comprehensive Data
	Ø	Ø	Ø	Ø
SVEN	0.023	-0.019	-0.182	-0.103
SHEN	0.236	0.188	0.071	0.167
SHDN	0.025	0.044	0.009	0.082
MHEN	-0.094	-0.020	0.040	0.004
MHEY	-0.045	0.014	0.242	0.090
ShSHEN	-0.146	-0.207	-0.180	-0.241

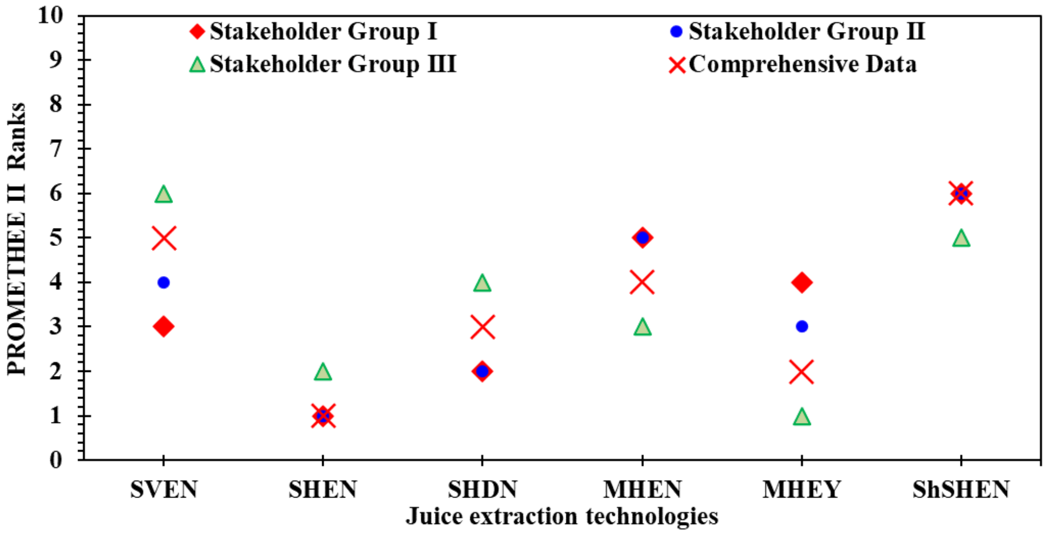


Figure 4.6 Ranking of alternative juice extraction technologies in PROMETHEE II

From *Figure 4.6*, it is observed that the alternative SHEN was best ranked according to stakeholder groups II and III. The same alternative was ranked second and alternative MHEY was best ranked according to stakeholder III. It also observed that alternative ShSHEN was least ranked according all three stakeholders, (which is the current practiced at Erode) for NCS production. The alternative MHEN was also reasonably least preferred according all three stakeholders. The alternatives SVEN & SHDN (the current traditional practices for NCS production at Anakapally) are comparatively least ranked for the sustenance of NCS industry. Also, from comprehensive data, SHDN & MHEY were observed be the best rank alternative juice extraction technology for NCS production.

Applying the steps of the VIKOR methodology, initially, the best and worst evaluation criteria values of alternatives are computed by considering the normalized payoff matrix. Then the values of utility measure (S) and regret measure (R) are calculated by considering the criteria weights accordingly. Further, the VIKOR index (Q) was calculated using Equation (13) and the values are as tabulated in *Table 4.10* Based on the increasing order of VIKOR index values the juice extraction alternatives are ranked by satisfying the condition 1 and 2 of Equation (14). *Figure 4.7* presents the alternative juice extraction ranking with respect to preferences of individual stakeholders in VIKOR.

Table 4.10 VIKOR index values of alternative juice extraction technologies

Alternatives	Stakeholder I	Stakeholder II	Stakeholder III	Comprehensive Data
	Q	Q	Q	Q
SVEN	0.370	0.272	0.777	1
SHEN	0	0	0.425	0.0351
SHDN	0.609	0.200	0.512	0.1925
MHEN	0.610	0.272	0.288	0.2851
MHEY	0.544	0.2	0	0.1149
ShSHEN	1	1	0.998	0.2459

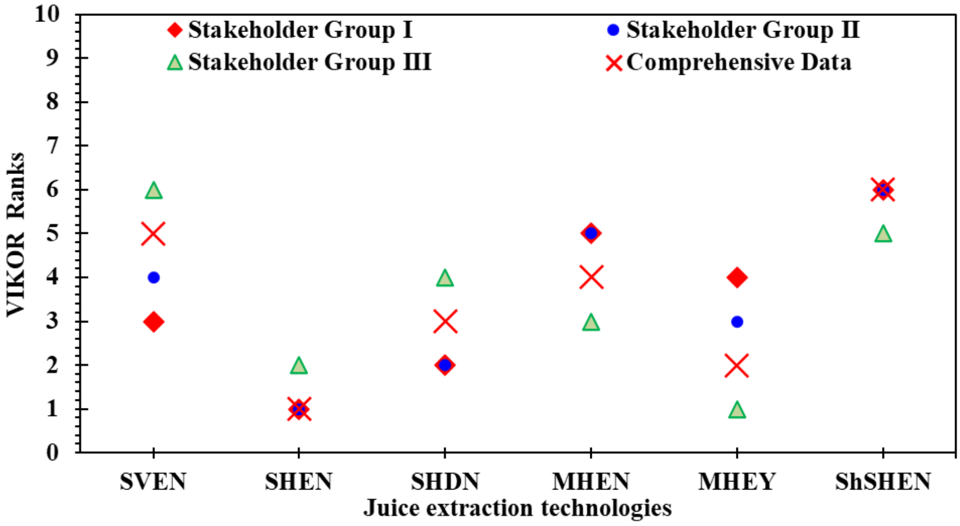


Figure 4.7 Ranking of alternative juice extraction technologies in VIKOR

From *Figure 4.7*, it is observed that alternative SHEN was best ranked with respect to stakeholder groups I and II. Similarly, with respect to stakeholder group III, the alternative MHEY was ranked best and alternative SHEN was ranked second. The current traditional practices using alternatives SVEN and SHDN (for NCS production at Anakapally) were comparatively least preferred for the sustenance of NCS industry. It also observed that alternative ShSHEN was least ranked according all three stakeholders, which is the current practiced at Erode for the sustenance of NCS industry. Also, from comprehensive data, SHDN & MHEY were observed be the best rank alternative juice extraction technology for NCS production.

As per the procedural requirement of ELECTRE I, initially, the data matrix is normalized to convert different units of various criteria into a common measurable unit. Then, the weighted normalized decision matrix is constructed to determine the concordance set and discordance set. Further, the net superior and inferior value are computed and tabulated in *Table 4. 11*. Finally, alternatives are ranked according to decreasing order of net superior value and increasing order of net inferior value. *Figure 4.8* presents the alternative juice extraction ranking with respect to preferences of individual stakeholders in ELECTRE I.

Table 4. 11 Assessment values of alternative juice extraction technologies in ELECTRE I

Alternatives	Stakeholder group I		Stakeholder group II		Stakeholder group III		Comprehensive data	
	C_a	D_a	C_a	D_a	C_a	D_a	C_a	D_a
SVEN	0.091	-0.144	-0.065	-0.064	0.084	-0.235	-0.226	0.106
SHEN	0.546	-0.555	0.354	-0.359	0.383	-0.424	0.282	-0.303
SHDN	0.082	-0.178	-0.051	-0.201	0.023	-0.284	-0.015	-0.204
MHEN	-0.293	0.360	-0.087	0.290	-0.152	0.303	-0.277	0.399
MHEY	-0.264	0.324	-0.003	0.073	-0.120	0.359	0.071	0.099
SShSHEN	-0.161	0.193	-0.150	0.261	-0.218	0.281	0.164	-0.097

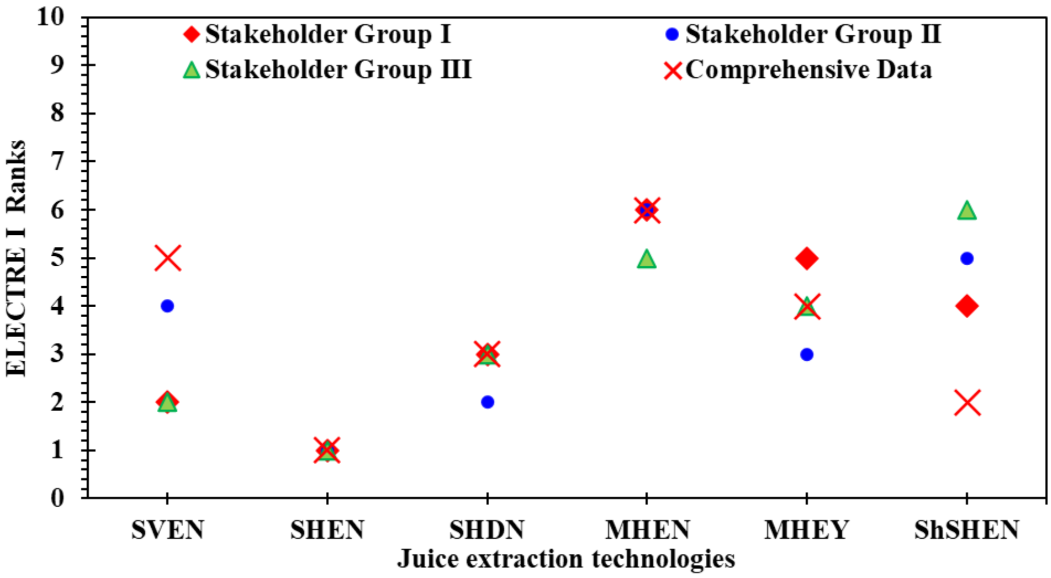


Figure 4.8 Ranking of alternative juice extraction technologies in ELECTRE I

From *Figure 4.8*, it is observed that alternative SHEN was best ranked with respect to all the three stakeholder groups and comprehensive data for both net superior (C_a) & net inferior (D_a). On the other hand, MHEN was comparatively least ranked with respect to all the three stakeholder groups and comprehensive data for both net superior (C_a) & net inferior (D_a). The current practice of using alternatives SVEN and SHDN are also comparatively least ranked with regard to all three stakeholders for NCS production.

The current traditional practices using alternatives SVEN and SHDN (for NCS production at Anakapally) were comparatively least preferred for the sustenance of NCS industry. It also observed that alternative ShSHEN was least ranked according all three stakeholders, which is the current practiced at Erode for the sustenance of NCS industry. Also, from comprehensive data, SHDN & MHEY were observed be the best rank alternative juice extraction technology for NCS production.

Results of the above three MCE analyses indicate that there exists a consistency (among all the three stakeholders' groups) in ruling out the possibility of using ShSHEN for NCS production. However, there has been an inconsistency (among all the three stakeholders' groups) in identifying the best possible alternatives for juice extraction techniques. This variation in ranking with respect to three stakeholders may be due to the approach followed in three different MCE techniques as well as the differences in priority for evaluation criteria by different stakeholder groups. For example, for stakeholder I, the factors namely, capital cost, energy cost, energy, and emissions were considered to be more important. Similarly, stakeholder group II, have given higher preferences to the criteria related to manufacturing aspects of NCS namely, capital cost, man-hours, quantity of juice, and brix, and so forth. Stakeholder group III has given higher preferences for the evaluation criteria related to the level of automation, quantity of juice, and process time. On the other hand, the comprehensive data consider all three stakeholder groups preferences equally. However, as demonstrated by

Srinivasa Raju in 2010; Gao et al in 2011; Saaty 2008, such an inconsistency in ranking could be addressed by considering “group decision by geometric mean” method to arrive at suitable and sustainable juice extraction technique (Srinivasa Raju 2010; Gao, Zhang, and Zhou 2011; Saaty 2008). As per this, if there are n ranks available for each of the alternatives, increasing order of geometric mean of these ranks for all the alternatives shall be useful for arriving at the final ranks of each alternative. As it could be seen from the above MCE for different stakeholder groups, there are nine ranks for each of the alternatives. *Table 4.* 12 gives information about the geometric mean values of ranks of the alternatives. *Figure 4.9* presents the final ranks of the individual alternatives, obtained by increasing order of this geometric mean values of the ranks.

Table 4. 12 Group decision values of alternative juice extraction technologies

Alternatives	Group decision value
SVEN	3.396
SHEN	1.379
SHDN	3.336
MHEN	3.107
MHEY	2.473
ShSHEN	6

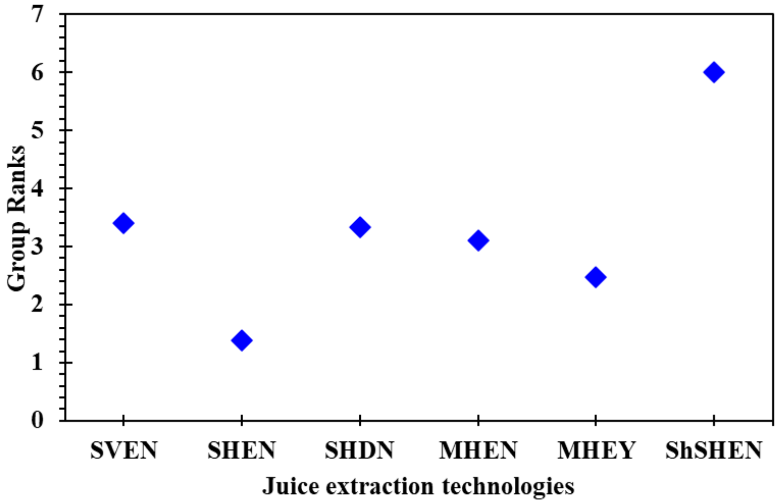


Figure 4.9 Group ranking of alternatives alternative juice extraction technologies

From *Figure 4.9*, it is observed that the alternative SHEN was found to be the most suitable juice extraction technique for the sustenance of NCS industry. Although the alternative SHEN extracts relatively small amount of juice, but then it satisfies all the three stakeholders' preferences for 11 evaluation criteria that come under sustainability, manufacturing, and production rate factors for the sustenance of NCS industry. In addition, it could be observed that alternative MHEY and MHEN are ranked 2 and 3, respectively. These suggest that both the above alternatives are the next best alternatives for NCS production. It was worth noting that, although the option MHEY was quite widely used in sugar industry, the present analysis suggests that MHEY may be used as an alternative in case SHEN cannot be opted d for any other reason. One of the possible reasons for alternative MHEY as a secondary option is due its high capital cost and CO_2 equivalent emissions. The current practice of alternative SHDN was ranked 4 and is less preferred for the sustenance of NCS industry. This may be due to its high-energy cost and low juice extraction efficiency. Similarly, the alternative SVEN, which is in current NCS production practice in few places of Andhra Pradesh, is not suitable for the sustenance of NCS industry due to its high crushing time, man-hours and energy required for sugarcane crushing. The alternative ShSHEN was the least preferred alternative for the sustenance of NCS industry, although this alternative is recently being used in upcoming NCS plants such as the one at Erode.

In essence, following are the conclusions that could be obtained from the undertaken MCE of various crushing techniques:

- Criteria weights computed indicate that capital cost, energy costs, quantity of juice, and man-hours are among the important criteria in identifying the suitable juice extraction techniques for NCS production.
- The crusher that uses shredders with six group priority weight with respect to all the stakeholders. Therefore, it is considered to be an inferior option for NCS production.

- Crusher with a single horizontal roller that uses electrical motor without any usage of hot water with 1.38 group priority weight, was found to be the most suitable and sustainable juice extraction technique for the sustenance of NCS industry.
- Crushers that are regularly used in the sugar industry, such as the ones that have multiple rollers with/without usage of hot water with 2.47 and 3.11 group priority weight, respectively, may be used as next alternatives only when the first alternative cannot be used for any other reason.
- The current and conventional technique of using single vertical roller that runs on electrical energy without the usage of hot water and single horizontal roller that runs on diesel engine and that does not use hot water were found be inferior option with 3.33 and 3.39 group priority weight, respectively and hence can be dispensed away with to produce NCS.

4.2 MCE of juice clarification process

In production of NCS, clarification is one of the most important sub-processes that eliminates the non-sugars impurities present in the extracted raw sugarcane juice that affects the quality of NCS. The quality and shelf-life of NCS mainly depends upon the type of clarification process, type of clarifiers and efficiency of clarification of sugarcane juice (Velásquez et al. 2019). Generally, vegetable or organic based clarifiers such as stem and root of green plants of deola and bhendi, seeds of castor, ground nut, soybean and etc. Inorganic or chemical based clarifiers like sodium hydrogen sulfite (hydros), calcium oxide (lime), sodium carbonate, sodium bicarbonate, and super phosphate are used. The major problem with the use of chemical clarifiers is that there is no well-prescribed level of clarifiers usage and there is always a possibility of adding these chemicals beyond the safety confines for human consumption. Sulfur dioxide is the most common clarifier that result in sulfates and organic sulfur that are dangerous for human beings. The cost of organic NCS is estimated to be 25%

higher than that of inorganic clarifiers(Rakesh Kumar and Kumar 2018). In order to increase the business potential of NCS, the manufactures are adding chemical clarifiers at undefined rate during clarification which is not suitable for human consumption. In order to replace these inorganic clarifiers and to improve the quality and shelf-life of NCS, a wide verity of clarification methods is available in the regular practice and as well as in the literature(Shi et al. 2019; Solís-Fuentes et al. 2019; Jegatheesan et al. 2012; Chikkappaiah et al. 2017; Ogando et al. 2019). Some of these are, use of membrane technology, electrocoagulation, use of plant mucilage and centrifuge process with activated carbon. Among all, choosing a right clarification method is vital for producing quality NCS, that improve the shelf life and consumption of NCS. At the same time, the clarification method used should also satisfy several sustainable criteria. Hence, choosing a right clarification method is complex problem governed by several conflicting criteria.

The computation for suitable and sustainable clarification technology for NCS production is carried out, among 5 clarification technologies using MCE techniques and 11 criteria covering suitability elements. The methodology adopted for the selection of suitable & sustainable juice clarification technique for NCS production using MCE is shown in *Figure 4.10*.

4.2.1 Identification of evaluation criteria

Initially, several criteria were identified through some of the field and literature surveys covering three main sustainability criteria. Following “combining and separation of criteria” processes of classical principles of MCE, a comprehensive list of eleven evaluation criteria were arrived covering various sustainable factors viz. resources & environmental effects, techno-economic and process output parameters. The identified eleven evaluation criteria, and their nature (maximization or minimization, crisp or fuzzy) are listed in the *Table 4. 13*.

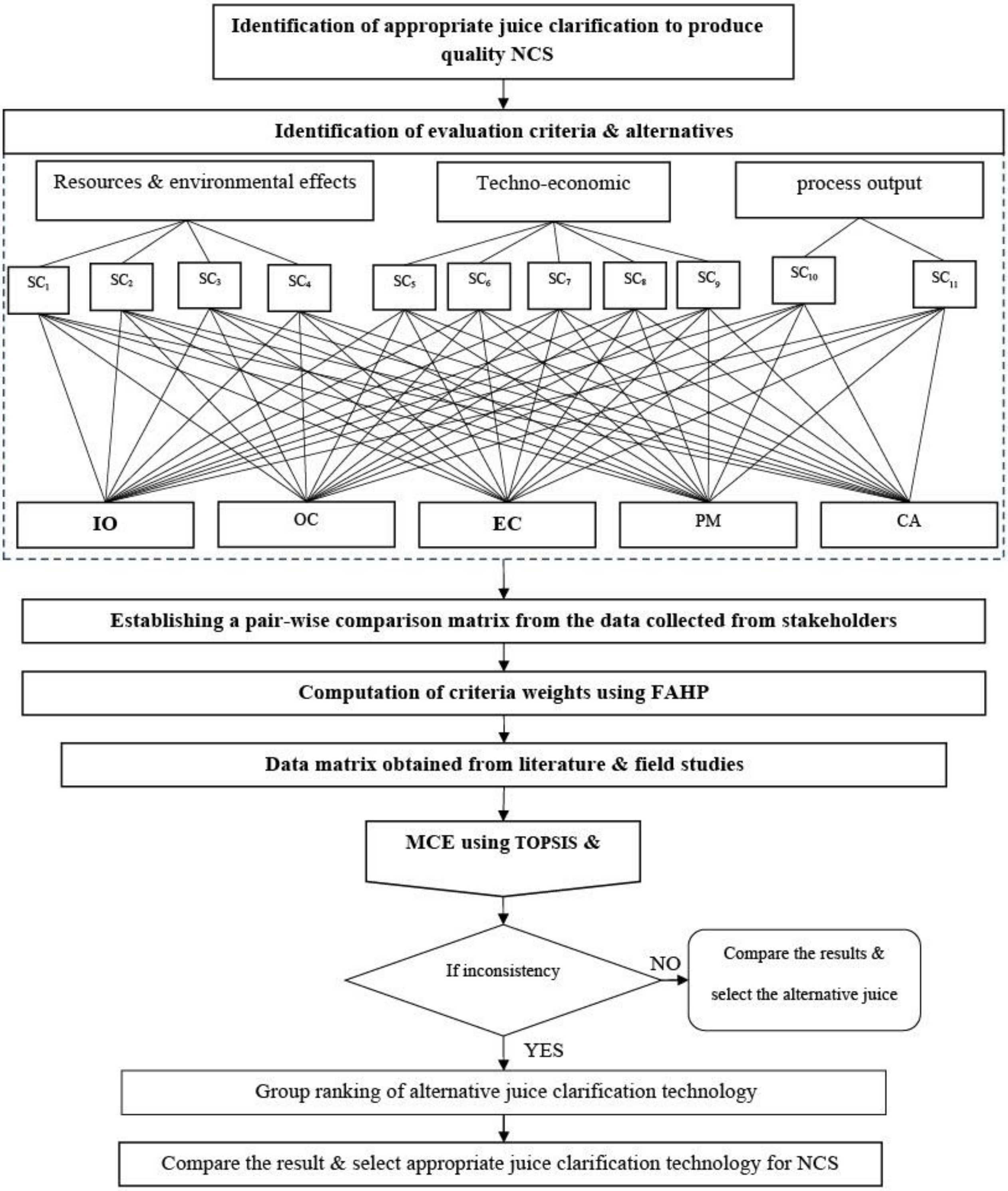


Figure 4. 10 Methodology for the selection of sustainable juice clarification for NCS industry

Table 4. 13 Evaluation Criteria for selection of sustainable clarification technology

Main criteria	Sub- Criteria		Max/Min
Resources and environmental effects	SC_1	Extent of organic clarificants	max.
	SC_2	Extent of inorganic clarificants	min.
	SC_3	Energy	min.
	SC_4	Human resource	min.
Techno-economic	SC_5	Economic budget toward Energy	min.
	SC_6	Initial investments	min.
	SC_7	Process activity	min.
	SC_8	Maintenance service	min.
	SC_9	Extent of automation (LOA)	max.
Process output parameters	SC_{10}	Scum removal	max.
	SC_{11}	ICUMSA colour	max.

4.2.2 Alternative technologies for juice clarification

After a thorough literature and field studies on the clarification practices that are followed in NCS production as well as in sugar industries, five clarification methods are found that may be considered to improve the present clarification processes for producing quality NCS. These are (i) Inorganic clarification (IOC) (ii) clarification by membrane filtration (MFC) (iii) application of electrocoagulation (EC) (iv) clarification by plant mucilage (PMC) (v) combined effect of centrifuge and use of activated carbon (CAC) (Shi et al. 2019; Solís-Fuentes et al. 2019; Jegatheesan et al. 2012; Chikkappaiah et al. 2017; Ogando et al. 2019).

Clarification by membrane filtration (MFC), the sugarcane juice is passed through sequence of membrane filters to remove the settable solids present under pressure. Application of these technology eliminate the usage of chemicals, particularly lime and produce superior quality clarified juice. Also, promises superior quality juice with better clarity, much lower viscosity and noticeable color removal. The alternative clarification process viz. electrocoagulation (EC) is based on the production of coagulating agent by electrical charge, such coagulation can aggregate impurities in the solution and remove them by flotation and sedimentation. Clarification by plant mucilage (PMC), specially (Aloe Vera plant) removes the maximum scum from the sugarcane juice with minimum process time. Also, helps in retaining more minerals salts and Phyto chemicals. Centrifugation with active carbon, is another clarification process, used to remove settable solids in the raw sugarcane juice, after then, is treated with the BAC for further clarification process. All these techniques of juice clarification vary with each other according to operation, energy source and also use of additional chemical for further filtration.

4.2.3 Computation of criteria weights

Weights of each evaluation criteria were derived using the FAHP method. It is for this reason that the information to establish the pairwise comparison matrix was partial and imperfect. Therefore, to avoid fuzziness given by information from different stakeholder groups, to establish a comprehensive pairwise matrix and to compute criteria weights, FAHP is applied.

Explain the reasons. Initially, a FAHP model, also known as decision hierarchy is developed for selection of sustainable juice clarification process (Kubler et al. 2016; Kaya and Kahraman 2010). In this model, the main objective "selection of sustainable juice clarifiaction" is positioned at the first level of decision hierarchy, main criteria and the sub criteria at next level followed by alternative juice clarification methods.

The computation of criteria using FAHP, is based on pair-comparison matrix. This comparison matrix is arrived at by comparing one criterion over another using Saaty's nine-point scale of relative importance. This information has been obtained from a group of stakeholders belonging to sustainability and academic promoters. Since criteria considered are fuzzy in nature and the opinions given by the group of stakeholders partial and imperfect, the pairwise comparison matrix obtained is fuzzified using triangular fuzzy membership functions. Then, a comprehensive pairwise matrix with respect to a group of stakeholders is obtained using the geometric mean method of Buckley(Buckley, Feuring, and Hayashi 2001). The comprehensive pair-wise comparison of eleven criteria with respect to the overall objective by a group of stakeholders is aggregated in *Table 4.14*.

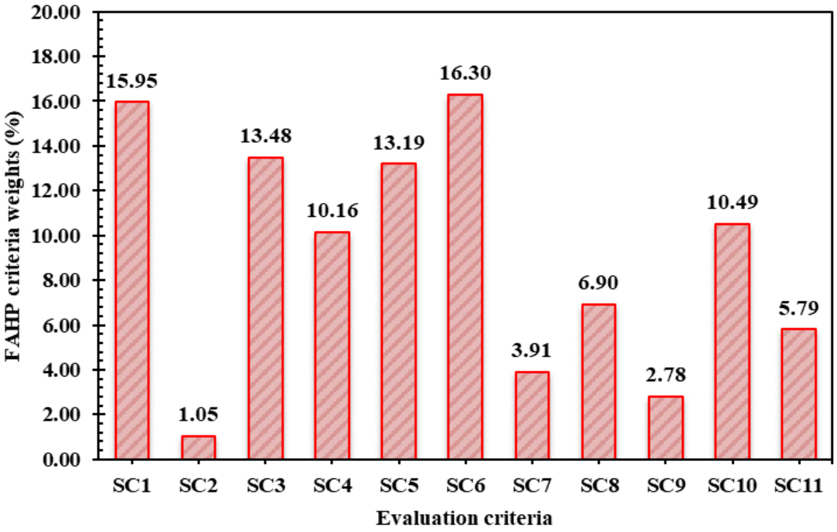


Figure 4. 11 FAHP weights of evaluation criteria for sustainable juice clarification process

Figure 4. 11 presents evaluation criteria weights for sustainable clarification process for NCS production. The CR for the obtained comprehensive pair-wise matrix is found to be 0.075. Since the CR is ≤0.1, the computed weights are considered for further assessing of alternative juice clarification technologies for NCS production(Saaty 2008). Among all 11 evaluation criteria, initial investments take the highest importance in deciding the suitability of clarification process for NCS production. Followed by this, are the extent of organic clarificants, energy, economic budget toward energy, human resource. With its weight of 0.01, extent of inorganic clarificants to improve the quality of NCS has become less important in deciding the suitability of clarification for NCS production.

Table 4.14 Comprehensive pair-wise matrix for juice clarification

	SC1	SC2	SC3	SC4	SC5	SC6	SC7	SC8	SC9	SC10	SC11
SC_1	(1,1,1)	(8.23,8.65,9)	(1.2,2.29,3.31)	(1.59,2.62,3.6)	(1.26,2.29,3.3)	(0.33,0.5,1)	(6,7,8)	(2.88,3.92,4.93)	(5.6,6.65,7.65)	(1,2,3)	(2.88,3.9,4.93)
SC_2	(0.14,0.1,0.7,)	(1,1,1)	(0.15,0.14,0.2)	(0.1,0.15,0.18)	(0.1,0.14,0.16)	(0.1,0.126,0.14)	(0.18,0.2,0.28)	(0.17,0.2,0.25)	(0.2,0.25,0.33)	(0.1,0.14,0.16)	(0.16,0.18,0.2)
SC_3	(0.31,0.43,0.79)	(6.32,7.32,8.3)	(1,1,1)	(1.59,2.6,3.63)	(0.33,0.5,1)	(0.33,0.5,1)	(4.31,5.31,6.3)	(2.5,3.557,4.57)	(5.6,6.65,7.65)	(1.26,2.29,3.3)	(3,4.5)
SC_4	(0.28,0.38,0.63)	(5.65,6.6,7.65)	(0.28,0.3,0.63)	(1,1,1)	(0.3,0.44,0.79)	(0.3,0.44,0.79)	(3.17,4.2,5.24)	(1.26,2.29,3.31)	(4.16,5.19,6.2)	(1,2,3)	(1.59,2.6,3.63)
SC_5	(0.31,0.44,0.79)	(6.3,7.32,8.32)	(1,2,3)	(1.26,2.29,3.3)	(1,1,1)	(0.3,0.44,0.79)	(4,5,6)	(4,5,6)	(4,5,6)	(1,2,3)	(2,3,4)
SC_6	(1,2,3)	(7.23,7.9,8.65)	(1,2,3)	(1.26,2.29,3.3)	(1.26,2.29,3.3)	(1,1,1)	(6.32,7.3,8.32)	(2.88,3.92,4.93)	(6,7,8)	(1.26,2.29,3.3)	(2.6,3.63,4.64)
SC_7	(0.13,0.14,0.17)	(3.63,4.645.65)	(0.16,0.19,0.2)	(0.19,0.24,0.3)	(0.16,0.2,0.25)	(0.15,0.14,0.21)	(1,1,1)	(0.3,0.44,0.79)	(1,2,3)	(0.15,0.18,0.2)	(0.46,0.6,0.87)
SC_8	(0.2,0.26,0.35)	(4,5,6)	(0.2,0.28,0.4)	(0.3,0.44,0.79)	(0.16,0.2,0.25)	(0.21,0.26,0.35)	(1.26,2.29,3.3)	(1,1,1)	(2.88,3.9,4.93)	(0.63,1.1,1.65)	(1.59,2.6,3.63)
SC_9	(0.13,0.15,0.18)	(3,4,5)	(0.13,0.15,0.1)	(0.16,0.19,0.2)	(0.16,0.2,0.25)	(0.13,0.14,0.16)	(0.33,0.5,1)	(0.2,0.26,0.35)	(1,1,1)	(0.13,0.1,0.17)	(0.18,0.2,0.29)
SC_{10}	(0.27,0.37,0.63)	(6.3,7.32,8.32)	(0.31,0.4,0.8)	(0.33,0.5,1)	(0.33,0.5,1)	(0.31,0.44,0.79)	(4.58,5.59,6.6)	(0.61,0.91,1.59)	(6,7,8)	(1,1,1)	(1.26,2.29,3.3)
SC_{11}	(0.21,0.26,0.35)	(4.31,5.31,6.3)	(0.2,0.25,0.33)	(0.28,0.38,0.46	(0.25,0.33,0.5)	(0.21,0.27,0.38)	(1.141.59,2.15)	(0.28,0.38,0.63)	(3.42,4.48,5.5)	(0.3,0.44,0.59)	(1,1,1)

4.2.4 Data formulation

In the present decision problem of identifying the sustainable juice clarification technology for NCS production, the required data for each alternative with respect to each criterion are not much found in the literature or through the field studies. However, MCE techniques viz. conventional AHP and TOPSIS were considered to obtain the required data for selecting the sustainable juice clarification technology for NCS production (Chikkappaiah et al. 2017) .

To obtain the required data for the alternative juice clarification technology with respect to each evaluation criterion by conventional AHP is based on the Liberatore five-point scale of outstanding (O), average (A), fair (F) and poor (P)(Naghadehi, Mikaeil, and Ataei 2009) . In which, a pair wise matrix was established by comparing each scale with the other and weight of scale viz. outstanding (O), average (A), fair (F) and poor (P) were found to be 0.513,0.261,0.129,0.063 and 0.034 respectively. Then the rating of alternative clarification technology with respect to each criterion is given based on a five-point scale by the stakeholders. *Table 4. 15* represents the rating of alternative method using Liberatore five-point scale. The priority of each alternative can be found by multiplying the weights of each criterion (found using FAHP) with weights of the alternative rating and adding the resultant value.

Table 4. 15 Rating of alternative method using Liberatore five-point scale

Evaluation Criteria	**Alternatives**				
	IOC	**MFC**	**EC**	**PMC**	**CAC**
SC_1	P	P	P	O	G
SC_2	O	A	A	G	A
SC_3	F	P	A	F	P
SC_4	P	A	A	P	F
SC_5	F	P	A	F	P
SC_6	G	P	F	G	P
SC_7	A	G	G	A	A
SC_8	O	P	P	O	P
SC_9	F	A	A	F	P
SC_{10}	A	G	G	O	O
SC_{11}	G	A	A	G	A

On the other hand, the method of ranking of alternative clarification technology by TOPSIS, a data matrix is generated by comparing each evaluation criteria with each alternative method and the priority are given by the stakeholder using 0-5 scale. *Table 4. 16* presents the data matrix using 0-5 scale.

Table 4. 16 Data matrix for juice clarification

Evaluation Criteria	**Alternatives**				
	IOC	**MFC**	**EC**	**PMC**	**CAC**
SC_1	0	0	0	5	4
SC_2	5	3	3	2	3
SC_3	4	5	3	4	5
SC_4	5	3	3	5	3
SC_5	4	5	3	4	5
SC_6	2	5	4	2	5
SC_7	3	2	2	3	3
SC_8	1	5	5	1	5
SC_9	2	3	3	2	3
SC_{10}	3	4	4	5	5
SC_{11}	4	3	3	4	3

4.2.5 Assessment and selection of alternative technology for juice clarification

The assessment and ranking of alternative juice clarification technologies for NCS production are done using conventional AHP and TOPSIS (*Figure 3.3 and Figure 3. 6*). The reason for considering these methods is because the data given in the data matrix is based on the liberatore five-point scale and priority scale of 0-5, wherein, these MCE techniques could efficiently decide the appropriate alternative(Naghadehi, Mikaeil, and Ataei 2009). The consistency in ranks are checked and finalized. The ranking of alternative methods using AHP is done based on Liberatore five-point scale and computed criteria weights. *Table 4. 17* shows the priority of each alternative method. The order of ranking is given a decreasing order of priority weights of alternative methods. Further, the ranking of alternative methods using TOPSIS is by generating the data matrix based on 0-5 scale and considering the computed criteria weights. The order of ranking is given according to the decreasing order of relative closeness to ideal positives.

Table 4. 17 Assessment values of alternative juice clarification technology

Alternatives	AHP	TOPSIS
IOC	0.013	0.51
MFC	0.007	0.22
EC	0.011	0.30
PMC	0.024	0.62
CAC	0.012	0.45

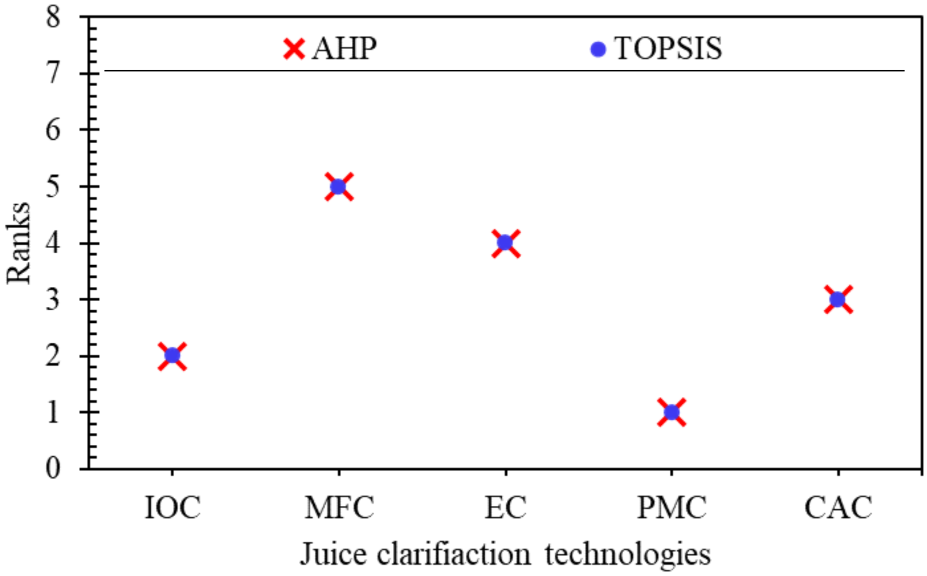


Figure 4. 12 Ranking of juice clarification alternative

From the *Figure 4. 12*, it is observed that clarification process with the use plant mucilage (PMC) is the most suitable and sustainable method for producing quality NCS. It may be due to low initial investments and mainly replacing the chemical that are dangerous to the human consumption. Also, it could be observed, the conventional practice of using inorganic clarificants (IOC) is comparatively least preferred for improving the quality of NCS. But can be used as secondary option by following the requirements of food standards. On the other hand, clarification with membrane technology (MFC), installed in few of sugar industries in Hawaii and South Africa, but it is least preferred for NCS production among all the alternatives considered, due to its high initial investment and high requirement of energy. Other main problem with this technology is that the membrane gets fouled which need to cleaned periodically. The other two alternatives electrocoagulation (EC) and centrifuge process with activated carbon (CAC) are not preferred much for clarification of sugarcane juice in NCS production, may be due to their high investment cost and high use of energy. Therefore, based on this some of the maximization and minimization evaluation criteria covering sustainability factors for five alternatives, the undertaken FAHP integrated with conventional AHP and TOPSIS based MCE suggest that clarification with plant mucilage is the most suitable and sustainable clarification method for improving the quality NCS.

In essence, following are the conclusions that could be obtained from the undertaken MCE of various clarification:

- Among the 11 evaluation criteria listed, initial investment and extent of organic clarifiers are the most important criteria in identifying the suitable method of clarification for improving the quality and shelf-life of NCS.
- The MCE techniques considered for the selection of clarification method and the evaluation conclude that clarification with plant mucilage is the most suitable and sustainable method of clarification for NCS production.
- On the other hand, the present practice of using chemical clarifiers is a relatively less preferred alternative for NCS production, but can be used as a secondary option by following the food standard requirements.

5. MCE of Technologies for Juice Evaporation Sub-Process

Keywords

Non-centrifugal sugar

Juice evaporation

Physio-chemical parameters

Striking point temperature

Juice evaporation sub-process, which is the subsequent process after crushing and clarification processes, could be considered as the heart of the conventional NCS production process. In the juice evaporation process the water in the juice is evaporated by supplying the necessary latent heat of vaporization by burning the bagasse available through the crushing process. The literature and field surveys suggest that there are multiple technologies by which this process can be achieved, although it is not scientifically known which one of these could be sustainable and suitable for producing quality NCS. Also, identifying the correct process conditions in terms of temperatures, concentration and other parameters would also be a subject of interest as this shall supplement the process of identifying the sustainable and suitable juice evaporation technology. As it will be presented in the subsequent sections of this chapter, both these problems could be seen as the candidates for the MCE. The works undertaken to get answers for these two questions are presented in this chapter.

5.1. MCE of juice evaporation process

In the production process of NCS, juice evaporation is an essential process in which extracted sugarcane juice is heated up to 115–120°C. Once the reaches this striking temperature and required concentration of 80-85^{o}Brix is achieved, the heat supply is stopped and juice is allowed to cool in an open atmosphere. The primary and essential purpose of this evaporation process is to evaporate a maximum quantity of water from sugarcane juice to get the required concentration of 80-85^{o}brix, which depends essentially on the type of evaporation method embraced. However, in the traditional NCS processing industry, a single or multiple (two/three/four) open pans fitted with an underground furnace is used, where the furnace is fired with bagasse (residue left after juice extraction). These units are in regular practice over decades, without bothering much about the thermal efficiencies of the system, the amount of bagasse utilized for combustion or the required concentration of juice, human and other resources. The published literature and field studies conducted suggest that there are a wide variety of evaporation technologies available in regular practice to produce NCS. Some of these are single pan evaporation technology, two pan evaporation technology, three pan evaporation technology, four pan evaporation technology, pans with fins, open pan heating with forced draft, multi-effect evaporator (regular use in sugar industries), and so on. The concentration achieved, the economics, the resource requirement, the environmental impact etc. shall be the guiding principles to identify the most suitable and sustainable ones among these available technologies. Of all these evaporation technologies, not all of them may satisfy all the required sustainability criteria. For instance, some have higher heat utilization efficiencies, some are costlier, some require higher resources, some are suitable for higher production volumes, some require more energy, some require more material for pan construction, some take less operational time, and so on. All the above imply that choosing the right juice evaporation technology is a complex problem governed by several mutually conflicting sustainability criteria for sustenance of the NCS industry, thereby qualifying it to be an MCE problem.

In the work presented here, the necessary MCE computations were carried out by considering 11 criteria covering four main sustainability criteria namely, (a) resources (b) technical (c) economic, and (d) process output and environmental parameters. To identify suitable and sustainable evaporation technology among 10 juice evaporation technologies Figure 5.*1* presents the methodology adopted for this.

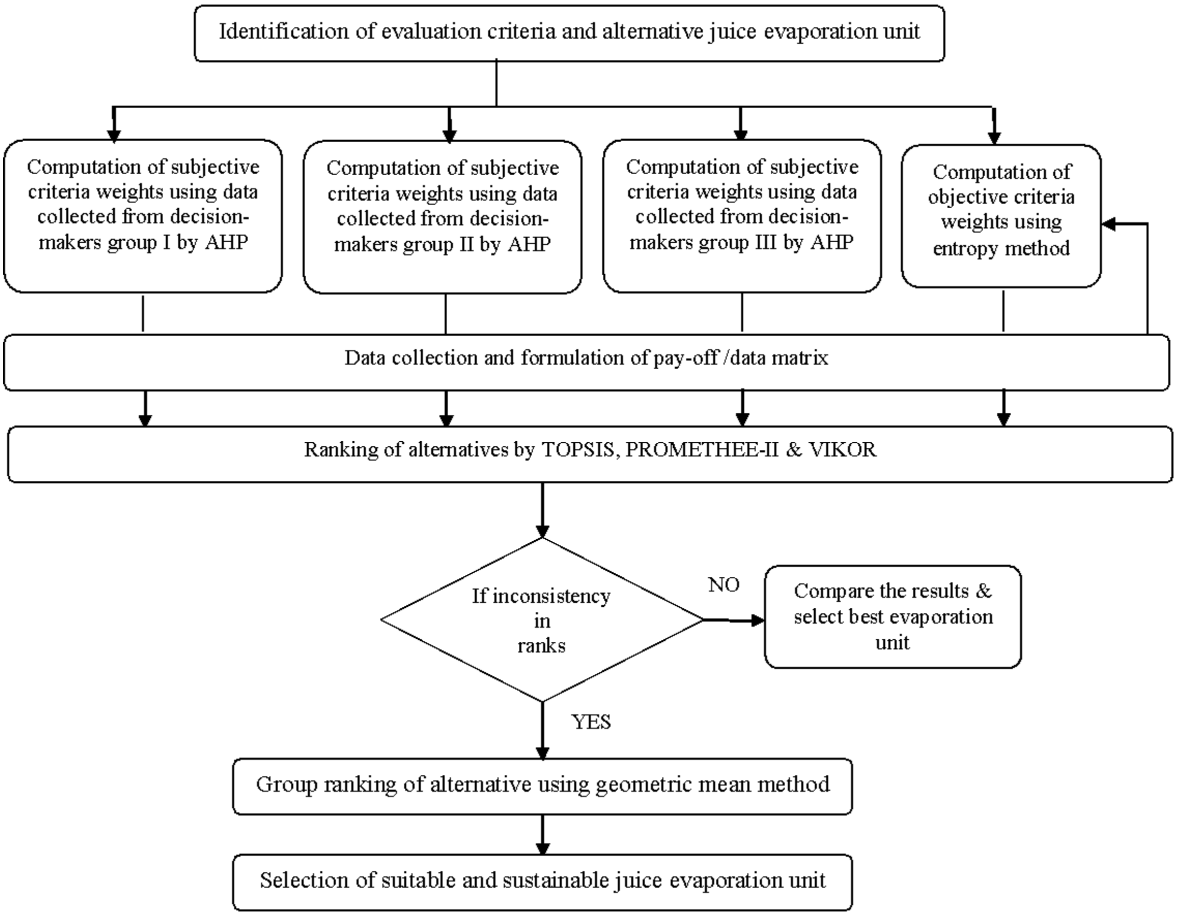


Figure 5.1 Methodology for the identifying a sustainable juice evaporation technology for NCS production

For the present MCE of identifying the sustainable juice evaporation technology, three stakeholder groups are considered viz. (i) academics and sustainability promotors (15 numbers), (ii) NCS manufactures (10 numbers) and (iii) NCS plant suppliers (3 numbers). The inputs from stakeholders are obtained through personal interviews, questionnaire-based surveys during field studies at Anakapally, AP, India (the well-established market for NCS for the last several decades) during March 6 to 12, 2019. Individual stakeholder groups inputs were considered for computing the subjective criteria weights using AHP. Additionally, the data obtained for each alternative juice evaporation technology with respect to each criterion were considered for computing the objective criteria weights using entropy method. Further, alternative juice evaporation technologies are assessed by MCE techniques viz. TOPSIS, PROMETHEE & VIKOR. The following sections describe the methodology adopted for identifying the sustainable juice evaporation technique for the NCS industry.

5.1.1. Identification of evaluation criteria

Keeping in view the definition of sustainability, four parameters have been identified for the present problem, namely (a) resources that cover the criteria related to human involvement and energy, (b) technical parameters that have direct/indirect bearing on the technical performance of the juice evaporation process, (c) economic issues that relate to the expenses required to carry out the juice evaporation process, (d) process output and environmental issues that designate the efficiency of evaporation process outcomes and its environmental impacts in and around the plant. Initially, to identify the appropriate evaluation criteria that govern the above-mentioned four elements of sustainability, questionnaires have been prepared based on the literature sources. The information for the questionnaires has been obtained from the field studies conducted at various prominent NCS cottage industries located in the southern part of India. As per the classical principles of MCE, the identified evaluation criteria must be complete, nonredundant, mutually exclusive, and should be minimum. Therefore, this theory has led to several “combination and separation of evaluation criteria” through multiple brainstorming meetings with various decision-makers. For instance, the criteria, namely “the quantity of fuel consumed” and “amount of juice evaporation,” are defined together as one criterion, namely “heat utilization efficiency.” Likewise, criterion, namely “evaporation process efficiency,” is defined in terms of “quantity of NCS” and “process time.” This systematic procedure has resulted in a detailed list of 11 performance criteria comprising four elements of sustainability. The 11 identified evaluation criteria, with their description and their definition of maximization or minimization, are described in *Table 5.1*.

Table 5.1 Description of evaluation criteria, with its nature and units for sustainable juice evaporation technology

Main criteria	**Sub Criteria**		**Definition**	**Units**	**Max/Min**
Resources	C_1	Man-hours	The cumulative time is taken by the total number of workers involved in the water removal process to produce the required NCS per day.	Hours/ day	Min
	C_2	Energy	The total energy (main and supplementary) per day is to be supplied for affecting the necessary evaporation of water from the sugarcane juice in the pan(s) to obtain the required NCS.	MJ/ day	Min
Technical	C_3	Heat utilization efficiency	The fraction of heat supplied is utilized to remove water from sugarcane juice to produce the required NCS.	%	Max
	C_4	Pan material requirement	The amount of raw material of pan(s) as a collective representation of number of pans, their dimensions and material required for construction.	kg	Min
	C_5	Design complexity	The measure of complexity in designs of equipment's/ sub-equipment's used in the process unit to obtain the required NCS, which is rated on a 1-5 scale, 1 being the lowest complexity and 5 being the highest complexity.		Min
Economic	C_6	Capital cost	The total initial cost of equipment and sub equipment's used in the process unit	₹	Min
	C_7	Energy cost	The total cost of the energy (main as well as supplementary) utilized per day to complete the juice concentration process.	₹/ day	Min
	C_8	Operational & maintenance (O&M) cost	The cost incurred per day to run the juice concentration process and keep the juice concentration unit and other accessories in good working condition.	₹ /day	Min
Process output & environmental	C_9	Quantity of NCS	The amount of NCS obtained per day through the water removal process.	kg/ day	Max
	C_{10}	Process time	Actual process time (hours) spent in a day to produce the NCS.	hours/ day	Min
	C_{11}	Greenhouse emissions	The total carbon dioxide equivalent emissions emerged out per day due to the consumption of energy source to complete the juice concentration process.	kg of CO_2 eq./ day	Min

5.1.2. Possible alternative technologies for juice evaporation

Juice evaporation is the most essential and crucial process in NCS production, which depends significantly on the type of evaporation method adopted. Ten different evaporation technologies have been identified through a comprehensive literature review and field observations, the details of which are illustrated in *Table 5. 2*. Also, the main findings related to juice evaporation technologies for the production of NCS are listed in *Table 5.3*. The schematic representation of these 10 evaporation technologies are detailed below.

Table 5. 2 Alternative juice evaporation technologies

Alternative	Type of pan	Number of pans	Conventional/Modified	Additional source of energy
ET_1	Open	1	Conventional	NO
ET_2	Open	1	Modified	NO
ET_3	Open	2	Conventional	NO
ET_4	Open	2	Modified	NO
ET_5	Open	3	Conventional	NO
ET_6	Open	3	Modified	NO
ET_7	Open	4	Conventional	NO
ET_8	Open	4	Modified	NO
ET_9	Closed	3	-	NO
ET_{10}	Open	1	Conventional	YES

Table 5.3 Main findings on juice evaporation technologies of NCS production

Publication	Description
(Esther et al. 2013).	A study of various energy losses in an actual traditional jaggery-making unit was conducted.
(Rao KSS 2003)	The thermal efficiency and bagasse usage of a traditional genuine jaggery manufacturing unit were assessed.
(Shiralkar et al. 2014)	An experimental investigation was conducted to calculate thermal efficiency, bagasse consumption, and air flow via traditional single-pan and multi-pan jaggery production furnaces
(Anwar 2010)	In a two-pan jaggery manufacturing furnace, fins at the bottom of the boiling and gutter pans were implemented to boost the efficiency of heat utilization
(Rajula Shanthy and Baburaj 2015)	In the manufacture of jaggery, the socio-economic impact of multiple pan furnaces over single-pan furnaces was investigated.
(Madan HK 2004)	A comparative performance trial was conducted on existing and improved three-pan jaggery production plants.
(Arya, Kumar, and Jaiswal 2013)	By implementing some constructional improvements, the performance of the three-pan jaggery producing plant was improved.
(Sardeshpande, Shendage, and Pillai 2010)	The performance of a four-pan jaggery unit under controlled bagasse fuel feeding was investigated.
(Jakkamputi and Mandapati 2016)	The use of solar energy to pre-heat sugarcane juice and the inlet air of a jaggery-making machine was investigated.

The traditional single pan evaporation technology (ET1) consists of an open pan placed on a furnace below the ground level, as shown in *Figure 5.2*(a). The heat from the furnace to the pan is transferred mainly through convection and radiation. The furnace used for this evaporation technology is made of ordinary masonry bricks, mud, and earth clay and an opening at the side of the furnace for the flow of flue gases with a continuous draft. This evaporation method requires comparatively less capital cost and has a relatively less heat utilization efficiency of 14.7%(Rao KSS 2003). The modified single pan evaporation technology, that is, alternative ET2, is similar to alternative ET1 but differs in furnace construction, as shown in *Figure 5.2*(b). The furnace here is made of fire bricks by maintaining the optimum height of the chimney for smooth flow of flue gases with control draft. The magnitude of the draft depends on the height and diameter of the chimney. The furnace made with fire bricks does not allow any leakage of heat. Also, the airflow rate is controlled by closing some of the air inlet holes for effective combustion of fuel. The evaporation technology with this modified furnace has thermal heat utilization efficiency of about 50–55% (Shiralkar et al. 2014). The production of NCS by this evaporation technology is almost three times the production capacity of alternative ET1.

Alternative ET3, the traditional two-pan evaporation technology, is the improvement of alternative ET1. Here, the second pan, known as the gutter pan, is placed after the boiling pan in the way of hot flue gases for preheating the sugarcane juice (as shown in *Figure 5.2*(c). The heat utilization efficiency of this evaporation technology is about 16.16%(Anwar 2010; Rakesh Kumar and Kumar 2018). Alternative ET4 (as shown in *Figure 5.2*(d)), the modified two-pan evaporation technology, is similar to alternative ET3 in the arrangement of pans and furnace construction. Still, both the open pans used to boil the juice are provided with parallel fins at the bottom to improve the heat utilization efficiency by 29.19% (Anwar 2010; Rakesh Kumar and Kumar 2018).

Similarly, alternative ET5 and ET6, the traditional and modified three pan evaporation technologies, respectively, consist of three open pans (shown in *Figure 5.2*(e, f)), one among is the boiling pan placed above the furnace, and the other two are gutter pan located in the direction of flow of hot flue gases for preheating the sugarcane juice)(Rajula Shanthy and Baburaj 2015). Furnace construction of alternative ET5 is similar to alternative ET1 with a heat utilization efficiency of 20.58% (Rajula Shanthy and Baburaj 2015). On the other hand, the furnace construction for alternative ET6 is similar to alternative ET2 with a heat utilization efficiency of 35%(Arya, Kumar, and Jaiswal 2013). Also, the alternative ET7 and ET8, the traditional and modified four pan evaporation technology, respectively, consist of four open pans (shown in *Figure 5.2*(g)) with furnace construction similar to ET1 and ET2, respectively(Sardeshpande, Shendage, and Pillai 2010).

Alternative ET9, an evaporation technology by multi-effect evaporators, is widely used in sugar industries and finds its application in one of the NCS plants near Erode, Tamil Nadu, India. This evaporation technology consists of multi-effect evaporators (three effect evaporators) arranged in series, as shown in *Figure 5.2*(h). The steam is generated in the boiler using wood as the fuel, and this generated steam is used to boil the sugar cane juice to get the required NCS. This method requires a comparatively high capital cost and has a relatively high heat utilization efficiency of 84.5%. The alternative ET10 (*Figure 5.2*(i)) is similar to alternative ET1 but integrated with solar collectors for preheating the sugarcane juice to improve the heat utilization efficiency is about 31.5% (Jakkamputi and Mandapati 2016). However, in all the evaporation technologies (except alternative ET9), the fuel (bagasse) required for the evaporation is fed into the furnace manually at regular intervals. The ash so formed during this evaporation process(Rao 1990). But all these methods of evaporation process vary from each other depending upon the type of pan used, the number of pans, constructional features of the furnace, and the additional source of energy used.

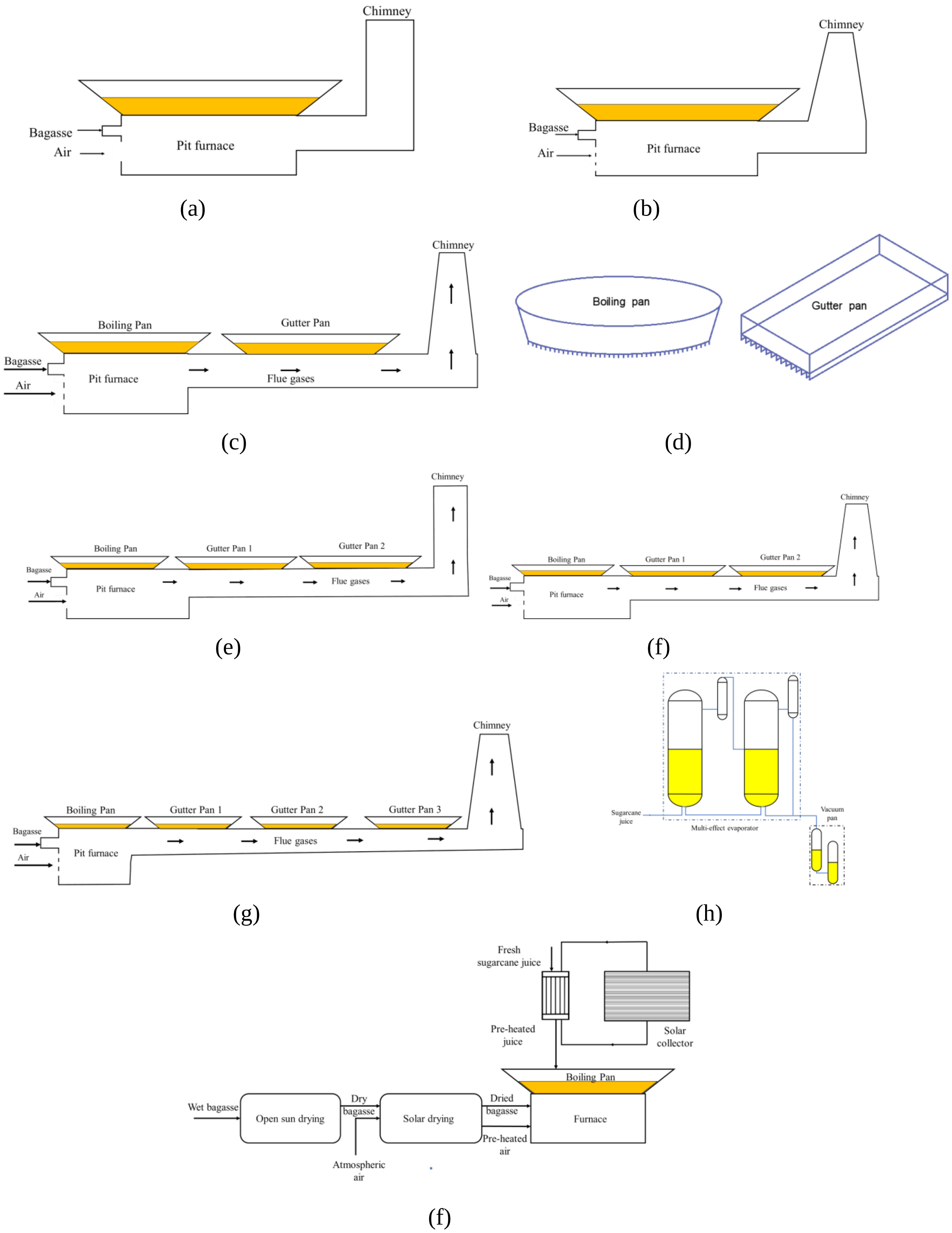


Figure 5.2 Various juice evaporation units for NCS production

5.1.3 Data formulation

The consolidated data matrix of 10 juice evaporation technologies for 11 evaluation criteria to produce the required quantity NCS per day through the evaporation process is given in *Table 5.4*. Data required for the alternatives ET1–ET8 are elicited from the field studies carried out at study areas, namely (a) Anakapalle, Andhra Pradesh during March 6–12, 2019, (b) Marayoor, Kerala during November 12–15, 2019, and also from various NCS cottage industries located in the southern part of India. The data obtained from these field studies are compared with related data presented in the published works Sardeshpande et al. (2010); Arya et al. 2013; Shiralkar et al. (2014); Rajula Shanthy et al. 2015 (Arya, Kumar, and Jaiswal 2013). Similarly, for alternative ET9, the data have been obtained during October 7–10, 2018, from one of the NCS production units located at Erode, Tamil Nadu, India. For alternative ET10, the data have been obtained from the published literature works (Jakkamputi and Mandapati 2016).

The data given in *Table 5.4* for each alternative juice evaporation technology in accordance with each evaluation criterion are self-explanatory in association with the definitions for the evaluation criteria given in *Table 5.1*. For instance, the energy required to produce a certain amount of NCS per day is obtained by considering (a) the calorific value of the fuel, (b) the amount of fuel required for producing 1 kg of NCS, (c) the quantity of NCS produced per day, as per the information obtained during the field studies. Furthermore, this information is compared and confirmed with the information given in published literature. Similarly, the data for the remaining evaluation criteria against each alternative evaporation technology are obtained.

Table 5.4 Data matrix for evaporation of sugarcane juice to obtain required NCS per day

Alternatives	**Sub criteria**										
	C_1	**C_2**	**C_3**	**C_4**	**C_5**	**C_6**	**C_7**	**C_8**	**C_9**	**C_{10}**	**C_{11}**
ET_1	22.5	29568	14.7	305	1	185000	6568	772	480	7.5	55.5
ET_2	19.35	21216	50	660	2	216350	5355	782.37	1180	10.3	35.2
ET_3	27	53416	16.16	816	1.5	230000	11684.75	1031	1214	10.5	88.5
ET_4	25.8	43704	29.19	985	2	333500	9560.25	1045	1214	10.1	71.02
ET_5	38.7	27553	20.58	785	2.5	347000	6051.15	1297	762	9.1	44.78
ET_6	38.7	29834	35	785	3.5	503150	6526.25	1318	937	9	48.5
ET_7	22.8	57360	25	847	2.5	413000	12547.5	1556	1500	8.5	93.21
ET_8	22.8	41520	29	847	4	578200	9082.5	1579	1500	8.5	67.47
ET_9	8	12214.2	84.5	1000	5	1500000	12919.8	1460	2000	8	42.6
ET_{10}	28	27480.52	31.5	305	4	350000	3380	2950.2	480	9.5	24.96

5.1.4 Computation of evaluation criteria weights

The decision hierarchy for the present decision problem of selecting a sustainable juice evaporation technology for NCS production in the MCE environment is presented in *Figure 5.3*. For the present MCE of identifying the sustainable juice evaporation technology, (a) subjective weight approach and (b) objective weight approach are considered. To improve the accuracy and to avoid any attempt to downplay the importance of evaluation criteria weights that influence the final assessment of alternatives and also to reflect results in a more scientific and reasonable method, both subjective preferences of stakeholder groups and objective data are considered and compared. Well-established and commonly used MCE techniques, namely the analytical hierarchy process (AHP) and entropy method, are considered for determining the subjective weights and objective weights, respectively.

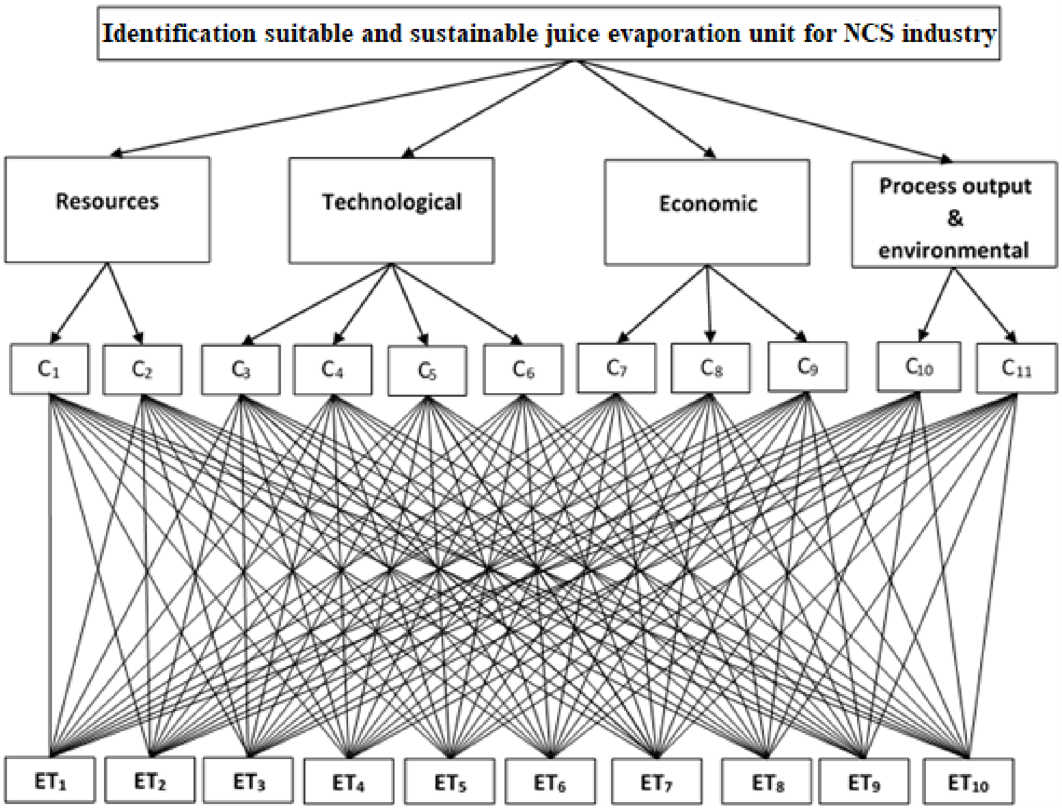


Figure 5.3 Decision hierarchy for the sustainable juice evaporation technology selection

The computation of criteria weights using AHP is based on the pairwise comparisons between two criteria by using Saaty's nine-point scale of relative importance (Saaty 2008). This information has been obtained from the above mentioned three stakeholder groups through personal interactions during field studies conducted on 6–12March 2019 at a study area viz. Anakapally, Andhra Pradesh, India. Pairwise comparison of each criterion as given by three stakeholder groups are as presented in *Table 5.5, Table 5.6 & Table 5.7.*

Table 5.5 Pairwise comparison matrix- Stakeholder group I

Sub criteria	C_1	C_2	C_3	C_4	C_5	C_6	C_7	C_8	C_9	C_{10}	C_{11}
C_1	1	0.5	1	3	1	0.5	0.5	1	0.5	2	2
C_2	2	1	1	2	2	0.5	1	2	1	2	1
C_3	1	1	1	2	2	0.5	1	2	1	3	1
C_4	0.33	0.5	0.5	1	1	0.5	0.5	1	0.5	1	0.5
C_5	1	0.5	0.5	1	1	0.5	1	2	0.5	1	0.5
C_6	2	2	2	2	2	1	2	2	2	4	2
C_7	2	1	1	2	1	0.5	1	2	2	3	2
C_8	1	0.5	0.5	1	0.5	0.5	0.5	1	0.5	1	0.5
C_9	2	1	1	2	2	0.5	0.5	2	1	2	1
C_{10}	0.5	0.5	0.33	1	1	0.25	0.33	1	0.5	1	0.5
C_{11}	0.5	1	1	2	2	0.5	0.5	2	1	2	1

Table 5.6 Pairwise comparison matrix- Stakeholder group II

Sub criteria	C_1	C_2	C_3	C_4	C_5	C_6	C_7	C_8	C_9	C_{10}	C_{11}
C_1	1	1	1	2	1	1	1	1	1	2	8
C_2	1	1	1	2	1	1	1	1	1	2	8
C_3	1	1	1	2	1	1	1	2	1	2	5
C_4	0.5	0.5	0.5	1	1	0.5	0.5	2	1	1	4
C_5	1	1	1	1	1	1	1	2	0.5	1	6
C_6	1	1	1	2	1	1	1	2	2	2	5
C_7	1	1	1	2	1	1	1	2	2	1	5
C_8	1	1	0.5	0.5	0.5	0.5	0.5	1	0.5	1	4
C_9	1	1	1	1	2	0.5	0.5	2	1	3	7
C_{10}	0.5	0.5	0.5	1	1	0.5	1	1	0.333	1	5
C_{11}	0.125	0.125	0.2	0.25	0.167	0.2	0.2	0.25	0.143	0.2	1

Table 5.7 Pairwise comparison matrix- Stakeholder group III

Sub criteria	**C_1**	**C_2**	**C_3**	**C_4**	**C_5**	**C_6**	**C_7**	**C_8**	**C_9**	**C_{10}**	**C_{11}**
C_1	1	1	0.33	0.33	0.25	0.33	3	3	0.33	0.5	6
C_2	1	1	0.5	0.5	0.5	0.5	2	3	0.5	0.5	8
C_3	3	2	1	1	2	1	2	5	1	1	5
C_4	3	2	1	1	1	0.5	4	4	1	1	5
C_5	4	2	0.5	1	1	1	3	3	1	1	6
C_6	3	2	1	2	1	1	3	4	2	2	6
C_7	0.33	0.5	0.5	0.25	0.33	0.33	1	2	0.33	0.5	5
C_8	0.33	0.33	0.2	0.25	0.33	0.25	0.5	1	0.25	0.25	4
C_9	3	2	1	1	1	0.5	3	4	1	1	9
C_{10}	2	2	1	1	1	0.5	2	4	1	1	7
C_{11}	0.167	0.125	0.2	0.2	0.167	0.167	0.2	0.25	0.111	0.143	1

The determination of objective weights by the entropy method is based on information theory, in which the criteria weights are derived objectively from the data matrix(Raman Kumar et al. 2021). The significant benefit of this approach is its objectivity. The assessment of alternative juice evaporation technology is based on a given 11 criterion that decides its relative significance without direct interference of the considered stakeholder groups.

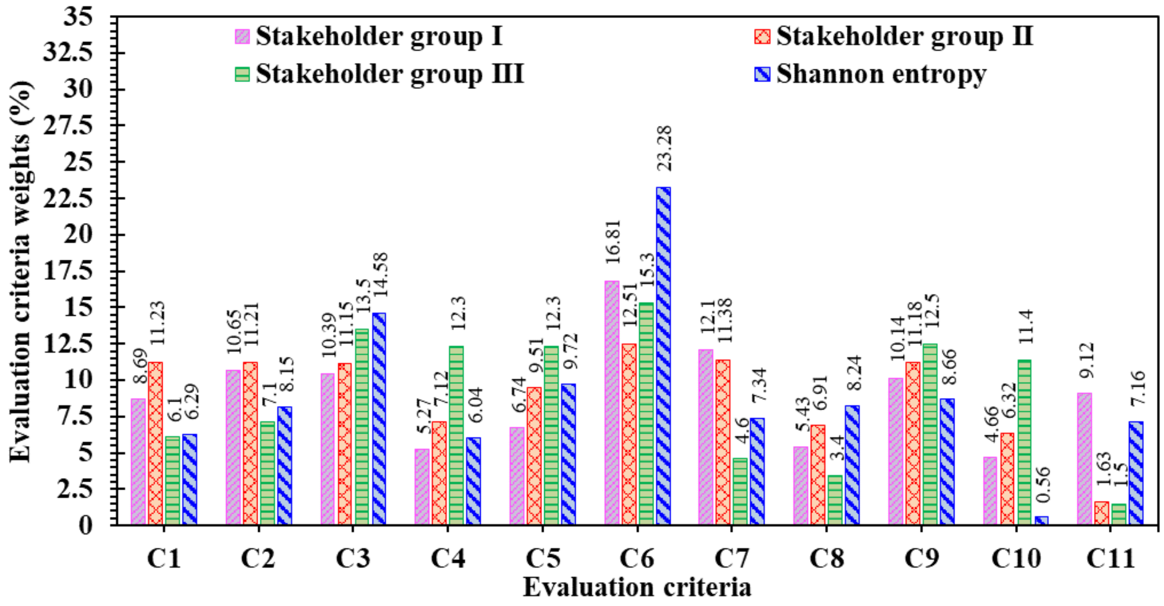


Figure 5.4 Evaluation criteria weights to assess the appropriate juice extraction technology

Figure 5.4 indicates the weights of 11 evaluation criteria with respect to three stakeholder groups and statistical data in the data matrix. It is observed that capital cost is the most essential criterion for all the stakeholder groups and also for the statistical data.

stakeholder group I, belonging to academic and sustainability promoters, have given more importance to sustainability elements. Therefore, energy-cost, energy and heat utilization efficiency are observed to be the more essential criteria. Likewise, stakeholder group II has given more importance to manufacturing elements involved in NCS production. Hence, energy cost, man-hours, and energy required are more essential criteria. Similarly, stakeholder III has given more importance to the efficiency/working of equipment/machinery. Therefore, heat utilization efficiency and quantity of NCS produced are observed to be more essential. However, statistical data, which are based on the data obtained for each alternative in reference to each criterion, found that heat utilization efficiency, design complexity, and quantity of NCS produced are more weighted criteria. These estimated criteria weights indicate that the considered decision-makers' priorities are more or less the same in relation to the statistical data. Furthermore, the degree of consistency for the priorities given by the decision-makers I, II, and III are measured to be 0.034, 0.028, and 0.033, respectively ($CR < 0.1$), indicating that weights obtained by the decision-makers are considered for further assessment along with the objective weights.

5.1.5 Assessment and selection of alternative technology for juice evaporation

The required computations to assess and select a sustainable juice evaporation technology for NCS production, three MCE techniques namely, TOPSIS, PROMETHEE II & VIKOR were considered. Why these methods are to be thoroughly explained here. The assessment by these MCE techniques require data formulated in the pay-off matrix and the evaluation criteria weights obtained by two MCE weight estimation methods viz. AHP & entropy method. The weights obtained by AHP for individual stakeholder groups and entropy weights statistical data are considered to obtain the assessment values by TOPSIS, PROMETHEE II & VIKOR.

Table 5.8 Assessment values of each alternative juice evaporation technologies in TOPSIS

Alternatives	Stakeholder I	Stakeholder II	Stakeholder III	Shannon entropy
	CC_j^*	CC_j^*	CC_j^*	CC_j^*
ET$_1$	0.632	0.576	0.580	0.645
ET$_2$	0.767	0.714	0.702	0.782
ET$_3$	0.577	0.526	0.564	0.629
ET$_4$	0.608	0.555	0.572	0.651
ET$_5$	0.604	0.524	0.532	0.622
ET$_6$	0.586	0.513	0.521	0.608
ET$_7$	0.542	0.502	0.548	0.598
ET$_8$	0.545	0.497	0.498	0.559
ET$_9$	0.528	0.576	0.462	0.424
ET$_{10}$	0.620	0.530	0.541	0.621

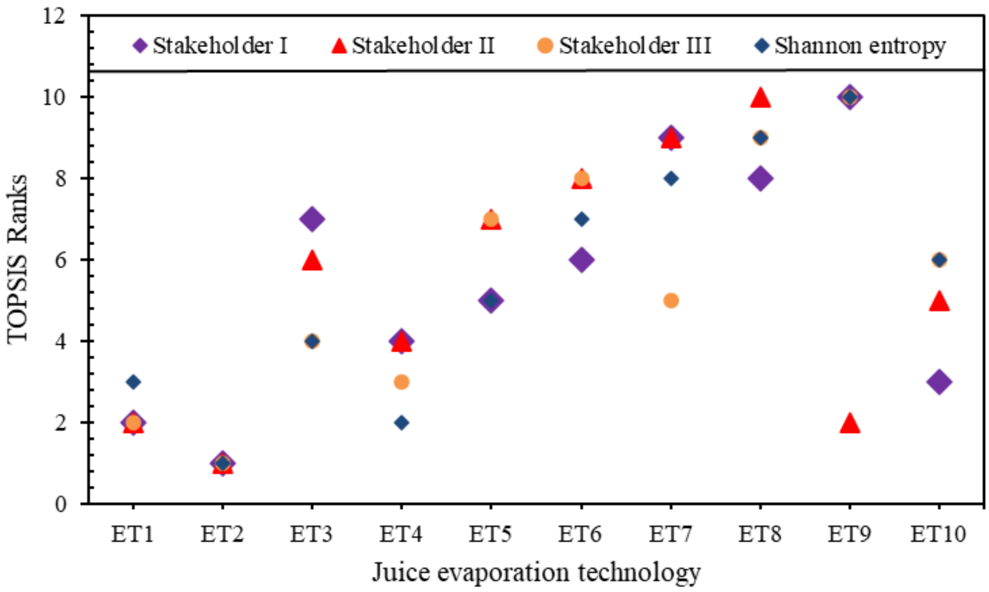


Figure 5.5 Ranking of alternative juice evaporation technology in TOPSIS

Figure 5.5 presents the assessment values of each alternative by TOPSIS with respect to three stakeholder groups and the statistical information. It is observed that a single pan with improved furnace construction (ET2) has been the best-preferred alternative for all the stakeholder groups and the statistical information. This may be due to the high thermal efficiency of the unit, low capital cost, and low greenhouse emissions. Also, it is observed that the alternative ET9, that is, evaporation of juice by a multi-effect evaporator, is the least promising technology for NCS production with stakeholder group I and III and also with the statistical data. This may be due to high capital and energy costs, though it has high thermal efficiency and production rate. The remaining juice evaporation technologies were comparatively less preferred for NCS production

Table 5.9 Assessment values of each alternative juice evaporation technologies by PROMETHEE II

Alternatives	Stakeholder I	Stakeholder II	Stakeholder III	Shannon entropy
	Ø	Ø	Ø	Ø
ET_1	0.124	0.147	0.185	0.118
ET_2	0.203	0.189	0.132	0.221
ET_3	-0.108	-0.105	-0.086	-0.039
ET_4	-0.041	-0.052	-0.070	-0.002
ET_5	0.011	-0.037	-0.046	0.007
ET_6	-0.008	-0.052	-0.057	-0.017
ET_7	-0.115	-0.094	-0.033	-0.089
ET_8	-0.041	-0.048	-0.045	-0.065
ET_9	0.035	0.063	0.029	-0.035
ET_{10}	0.063	-0.010	-0.009	0.019

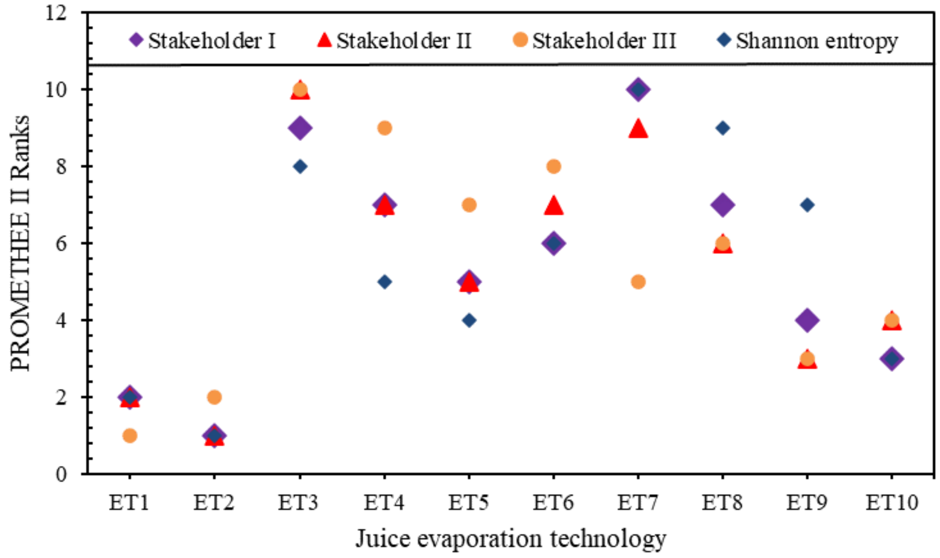


Figure 5.6 Ranking of alternative juice evaporation technology in PROMETHEE II

Table 5.9 presents assessment values of alternative evaporation units by PROMETHEE II, the ranking of alternatives is illustrated in *Figure 5.6*. It is observed that the alternative single pan with the improved furnace (ET2) is best ranked with respect to stakeholder group I and II and also with objective weights. The same alternative has been ranked second by stakeholder group III. This may be due to the high thermal efficiency of the unit, low capital cost, and low greenhouse emissions. The alternative ET1, the traditional single pan, has been observed to be the second-best alternative with stakeholder group I and II and also with, statistical data. The same has been ranked first with stakeholder group III. This may be due to low thermal efficiency and production rate, although it has a low capital cost. The alternative ET7, a traditional four-pan evaporation unit, is the least ranked with stakeholder group I and statistical data. The same has been ranked 9th with stakeholder group II, maybe due to high capital cost and low thermal efficiency of the unit. The alternative ET3, a traditional two pan evaporation technology, is the least ranked with stakeholder group II and III. A traditional two-pan evaporation unit is the least ranked stakeholder group II and III and has been ranked 9th with statistical data.

Table 5. 10 Assessment values of each alternative juice evaporation technologies in VIKOR

Alternatives	Stakeholder I	Stakeholder II	Stakeholder III	Shannon entropy
	Q	Q	Q	Q
ET_1	0.343	0.470	0.343	0.411
ET_2	0.000	0.000	0.192	0.000
ET_3	0.712	0.881	0.818	0.643
ET_4	0.496	0.629	0.685	0.497
ET_5	0.468	0.783	0.670	0.540
ET_6	0.473	0.808	0.447	0.483
ET_7	0.772	0.879	0.571	0.665
ET_8	0.497	0.625	0.525	0.600
ET_9	0.766	0.714	0.787	0.913
ET_{10}	0.426	0.737	0.613	0.449

Table 5. 10 presents assessment values of alternative evaporation units by VIKOR, and accordingly ranking of alternatives is illustrated in *Figure 5.7* . It is observed that the alternative single pan with improved furnace design (ET2) has been the best ranked with all the three stakeholder groups and also with the statistical data, may be due to high thermal efficiency of the unit, low capital cost, and also low greenhouse emissions. On the other hand, the evaporation of juice by a multi-effect evaporator (ET9) has been ranked 10th with stakeholder group I and statistical data. The same has been ranked 9th with stakeholder group III, indicating the least favorable technology for NCS production. It could be because the alternative ET9 comparatively has high capital and energy cost, which are the most preferred criteria by all the stakeholder groups. The alternative ET3, a traditional two-pan evaporation unit, is the least ranked with stakeholder group II and III and has been ranked 8th with statistical data. It may be due to higher greenhouse emissions. Also, the current traditional practice using ET1 is ranked 2nd with all the three stakeholder groups and the statistical data, maybe because of the high thermal efficiency of the unit, low capital cost, and low greenhouse emissions.

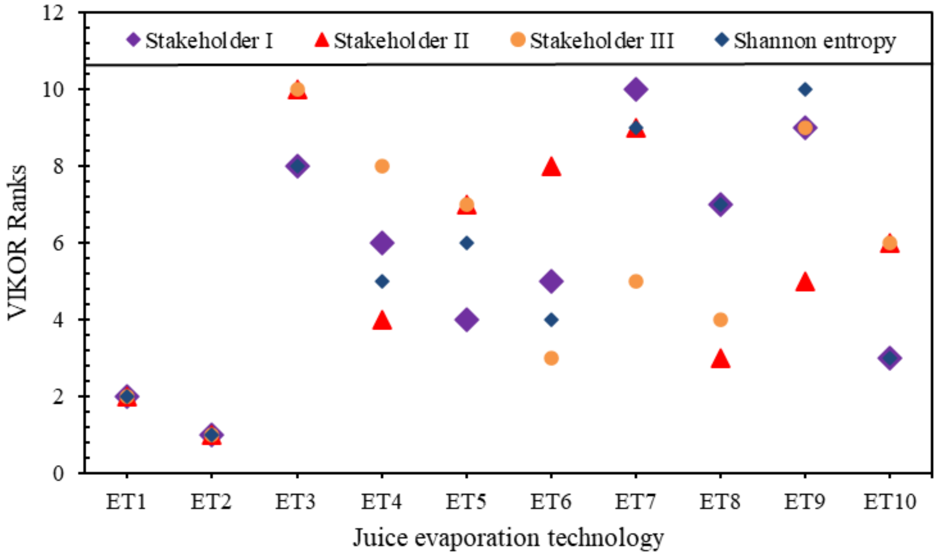


Figure 5.7 Ranking of alternative juice evaporation technology in VIKOR

The outcomes of the above MCE evaluation imply that there has been an inconsistency in the ranks of alternative juice evaporation technologies. This inconsistency in each alternative juice evaporation technology ranks may be due to the three different criteria weights and methodology of three MCE methods. Such a variation in the ranking pattern of alternatives can be analyzed by computing the “group decision by the geometric mean method.” Initially, the group decision is obtained by performing the geometric mean method for the ranks of three weights approaches in each MCE method. *Table 5. 11* presents the final ranks of alternative juice extraction technologies with respect to the three MCE methods.

Table 5. 11 Group decision values of alternative juice evaporation technologies

Alternatives	Group decision value
ET$_1$	1.93
ET$_2$	1.08
ET$_3$	7.66
ET$_4$	5.01
ET$_5$	5.94
ET$_6$	5.12
ET$_7$	8.32
ET$_8$	7.11
ET$_9$	6.69
ET$_{10}$	3.34

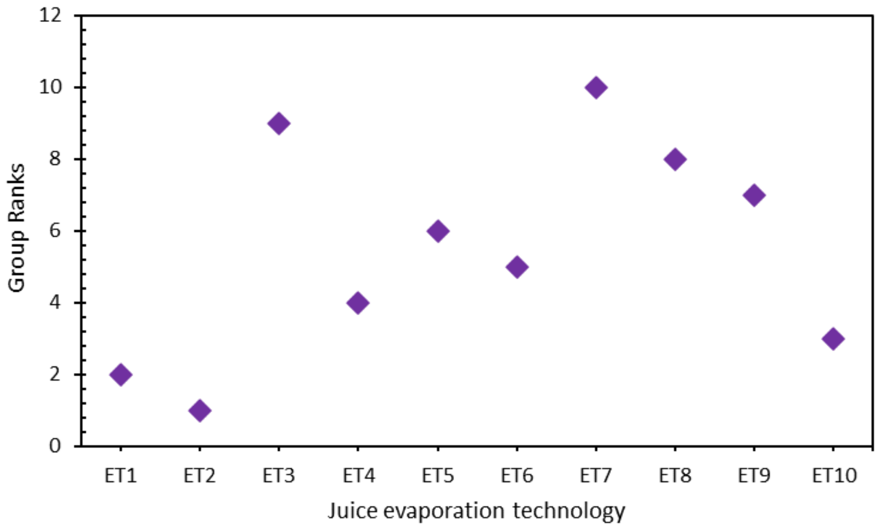


Figure 5.8 Group ranking of alternative juice evaporation technologies

It is observed from *Figure 5.8* that the alternative ET2, a single pan with an improved furnace, is found to be the most sustainable juice evaporation unit for the production of NCS.

This is because the alternative ET2 satisfies all the sustainability elements for NCS production. It is also observed that the alternative ET1, the traditional single pan evaporation unit, which in the current practice at Anakapalle, is found to be the second-best alternative for producing NCS and may be used as an alternative for ET2. This may be due to the high thermal efficiency of the unit, low capital cost, and low greenhouse emissions. On the other hand, the alternative ET3 and ET7 and evaporation of juice by traditional two pan and four pan units are ranked 9th and 10th, indicating that these alternatives are the least promising technologies. This is due to its high capital and energy cost, low thermal efficiency, though having high production rate. The alternative ET10, a traditional single pan integrated with solar collector, is ranked 3rd and comparatively less preferred because of the low production rate and complexity in design. The current alternative ET4, the modified two pan unit, comparatively less preferred unit with 4th rank. This maybe of high capital cost and design complexity. ET5 and ET6, the traditional and modified three pan evaporation units, are less preferred alternatives with 6th and 5th ranks, respectively. This may be due to its low heat utilization efficiency and high man-hours required for the production of NCS. Similarly, modified four pan evaporation unit (ET8) and multi-effect evaporation unit (ET9) are least preferred with 8th and 7th ranks, respectively. This may be due high capital cost and material requirement with complex design, although having high heat utilization efficiency and production rate. Based on these stepwise MCE analyses using 11 evaluation criteria covering four sustainability elements, juice evaporation using a single pan with a modified furnace (ET2) has been observed to be the most sustainable juice evaporation unit for the production of NCS.

5.2 MCE for identification of appropriate process condition for quality NCS

Apart from identifying the appropriate evaporation technology for NCS production, it is also necessary to know the suitable production process condition during the evaporation process. The production process conditions include the striking point temperature and appropriate clarificant to use to produce the quality NCS(Ogando et al. 2019). The “striking point” is the exact temperature at which the heat supply to the juice (and hence the boiling of the juice) is to be stopped. This “striking point”, which varies from 110°C to 125°C depending on the type of clarificant used, has a more significant influence on the kinetics of color change and other quality parameters that may lead to caramelization of various monosaccharides with heating time (M. v. Rane and Uphade 2017) . For instance, organic clarificant namely Aloe vera mucilage with 125°C striking point results in NCS with low moisture content (6.36%) with a more attractive golden-yellow color but requires more heating time (51minutes). Similarly, another combination (Aloe vera mucilage,110°C) results in NCS with higher moisture content (12.27%) with good taste and attractive golden-yellow color and yet another combination (120°C) results in NCS which requires more energy supply (0.8kWh).

MCE methods could be used to analyses the data obtained while producing NCS with different clarifiant-striking temperature combinations. Also, demonstrates how these MCE could be used to obtain the best clarificant-striking temperature combinations to produce quality NCS. The necessary data was generated by producing different NCS samples in the laboratory, for different clarificant - striking point combinations. The physicochemical quality parameters and process variables of the NCS samples were measured using appropriate measuring tools and methodologies. Finally, these measured quality parameters and production process parameters were subjected to MCE analysis to arrive at appropriate process conditions for producing quality NCS.

The methodology adopted for identifying the appropriate process conditions for producing quality NCS using MCE is shown in *Figure 5.9*. The following sections give the complete details of these.

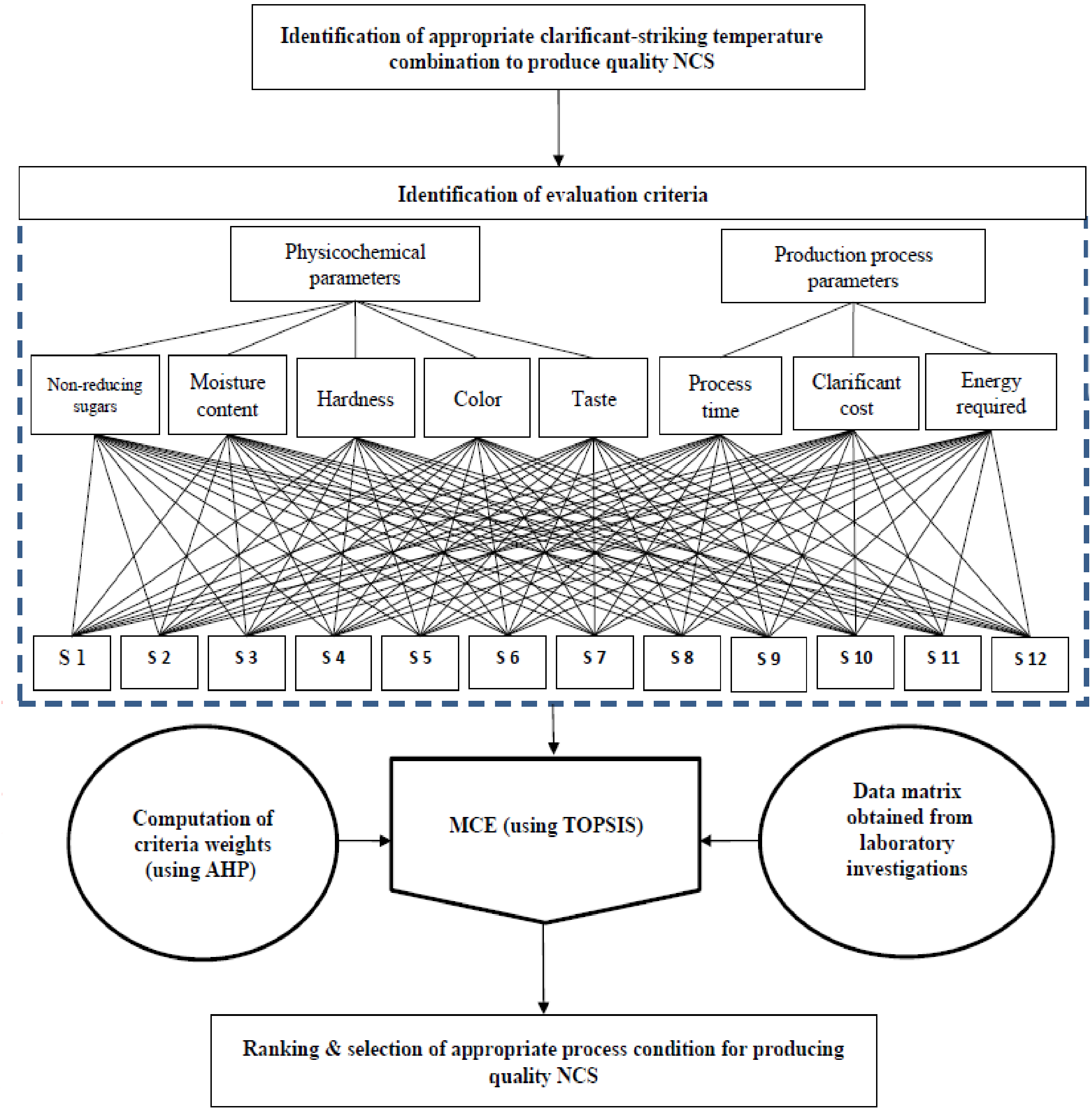


Figure 5.9 Methodology for the identifying appropriate process condition for producing quality NCS

5.2.1 Identification of evaluation criteria

In a techno-commercial sense, the so produced NCS is designated with “grades” (such as Grade I, Grade II etc.), which are differentiated with each other w.r.t. different physicochemical quality parameters such as color, hardness, crystalline structure, etc. The significant features that decide/increase the acceptability of NCS by the end users are its physical characteristics such as hard and crystalline structure, color (i.e., closeness to golden yellow), taste and flavor. The chemical factors that affect these physical characteristics are sucrose content, reducing sugar content, moisture content etc. In addition, the other factors such as, type of sugarcane, fertilizers used, sugarcane juice boiling temperature, process/heating time, methods adopted for drying, packing and storage also have a greater impact on the quality of NCS. These physicochemical quality parameters of NCS exhibit a close relationship with the type of clarifiers used and striking point temperature of sugarcane juice (Deotale et al. 2019).

Initially, several criteria were identified through some of the field and literature surveys covering physicochemical parameter that define the quality of NCS and production process parameters that define NCS production process. Following classical principles of MCE, a comprehensive list of evaluation criteria was arrived covering various physicochemical parameter and production process parameters (Pearman 2009). For instance, criteria namely, “non-reducing sugars” and “reducing sugar” are independent in defining the quality of NCS and hence considering one of these is sufficient as per the theories of the MCE analysis. The identified eight evaluation criteria, and their nature (maximization or minimization, crisp or fuzzy) are listed in the *Table 5.12*.

Table 5.12 Evaluation criteria and their nature for identifying appropriate process condition for producing quality NCS

Main criteria	Sub Criteria		Units	Maximum/ Minimum
Physicochemical parameters	C_1	Non-reducing sugars	%	Minimum
	C_2	Moisture content	%	Minimum
	C_3	Hardness	kgf	Maximum
	C_4	Color	-	Maximum
	C_5	Taste	-	Maximum
Production process parameters	C_6	Process time	Minutes	Minimum
	C_7	Clarificant cost	₹	Minimum
	C_8	Energy required	kWh	Minimum

5.2.2 Computation of evaluation criteria weights

For the present MCE of identifying the appropriate process condition for NCS production, well-established and commonly used MCE technique viz. AHP is considered for determining the weights of evaluation criteria. As per AHP methodology, each criterion was compared with others using Saaty’s nine-point scale of relative importance, to form a pairwise comparison matrix. The data for generating this pairwise comparison matrix was obtained from a panel of experts comprising of researchers and academics working in the relevant areas, NCS producers and end users, through personal interviews, questionnaire-based surveys and brainstorming exercises which happened during the period from 2nd to 18th March 2020. The criteria weights were then computed by following the established process. As required by the AHP methodology, the computed criteria weights were checked for their consistency by computing consistency ratio (CR). In the cases, when the CR was greater than 0.1, the panel was re-consulted, fresh data was obtained, pairwise comparison matrix was re-formed, weights were re-computed and the CR was re-checked and the process was repeated till the satisfactory results were obtained. *Table 5.13* presents the final comprehensive pairwise comparison matrix obtained for calculating the criteria weights for the present decision problem.

Table 5.13 Comprehensive pairwise comparison matrix

Sub criteria	**C1**	**C2**	**C3**	**C4**	**C5**	**C6**	**C7**	**C8**
C1	1	3	4	5	2	7	6	8
C2	0.33	1	2	3	0.5	5	4	6
C3	0.25	0.5	1	2	0.33	4	3	5
C4	0.2	0.33	0.5	1	0.25	3	2	4
C5	0.5	2	3	4	1	6	5	7
C6	0.14	0.2	0.25	0.33	0.17	1	0.5	2
C7	0.17	0.25	0.33	0.5	0.2	2	1	3
C8	0.13	0.17	0.2	0.25	0.14	0.5	0.33	1

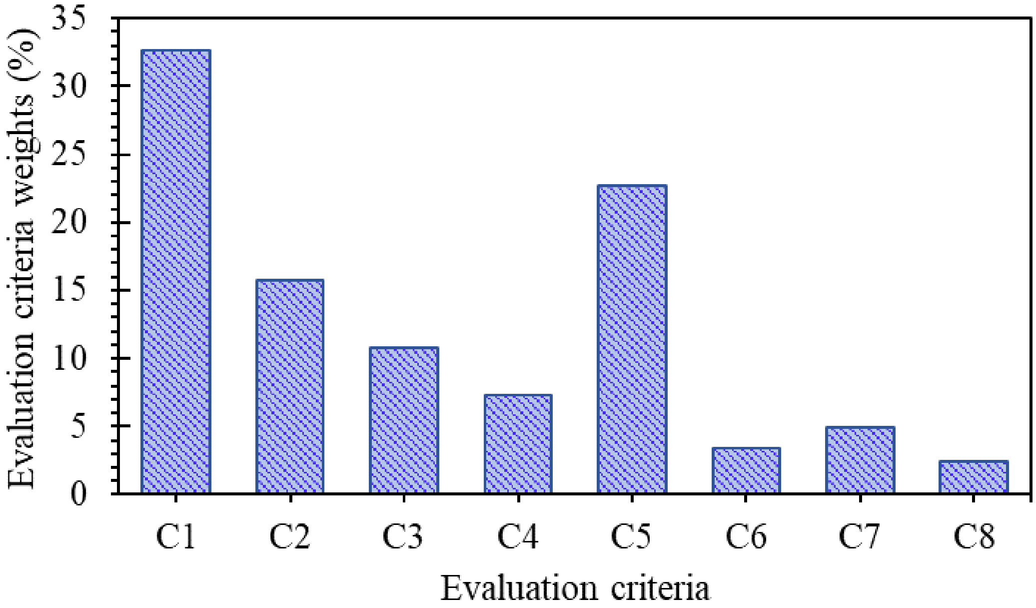


Figure 5.10 Weights of evaluation criteria for selection appropriate process condition for producing quality NCS

The computed weights of eight evaluation criteria covering the physicochemical and production process parameters are given in *Figure 5.10*. The consistency ratio, CR for these weights computed using AHP was found to be 0.054, which was less than the limiting value of

0.1, indicating that the computed weights are in order as stipulated by the norms of the AHP. Among all the evaluation criteria, physicochemical parameters viz. non-reducing sugars, taste, and moisture content carry higher weightages for identifying the appropriate clarifiacnt-striking temperature combination to produce quality NCS. Comparatively, the production process parameters viz. process time, clarificant cost, and energy required carry a lesser weightage.

5.2.3 Alternative process condition for quality NCS production

Field and literature studies indicate that NCS is produced with (a) no clarificants (example: NCS produced in production units in Marayoor, Kerala, India) (b) Inorganic/chemical clarificants (such as Sodium hydrogen sulphite knows as hydros, the extensively used one for its ability to produce NCS with attractive golden-yellow color) (c) Organic clarificants (such as stems and roots of bhendi, mucilage of Aloe vera mucilage, seeds of soybean/ castor/ groundnuts etc) (Patil et al. 1999). Use of different clarificants have different influences on the quality and marketability of the NCS produced. For instance, use of organic clarificants retain more nutritious contents of NCS compared to the one produced using inorganic/chemical clarificants (Rakesh Kumar and Kumar 2018). However, NCS produced using organic clarificants is 25% more costlier than the one produced using inorganic clarificants. On the other hand, to improve the color and arguably, the other quality parameters, chemical clarifiers are used at an undefined rate, which is not appropriate for human consumption (P. V. K. Jagannadha Rao, Das, and Das 2009) .

For the MCE problem of identifying the appropriate process condition for NCS production, three clarification processes viz (a) no clarificants (as done in many NCS production units in Marayoor, Kerala, India) (b) Inorganic/chemical clarificant (Sodium hydrogen sulphite knows as hydros, as used extensively in many of the NCS production units across India) (c) Organic clarificants (mucilage of Aloe vera mucilage as suggested in published literatures (Chikkappaiah et al. 2017). As sourced from the published literature (for example, (P. Jagannadha Rao, Das, and Das 2007), typically, the striking temperature for the NCS preparation ranges from 110°C to 125°C. Accordingly, 110°C, 115°C, 120°C & 125°C were considered as the striking temperature for the NCS sample preparation. *Table 5.14* represents the clarificant- striking temperature combinations for the twelve NCS samples.

Table 5.14 Clarificant-striking temperature combinations for preparing NCS samples

NCS Sample	Temperature (^oC)	Clarificant
S1	110	No clarification
S2	115	No clarification
S3	120	No clarification
S4	125	No clarification
S5	110	Hydros
S6	115	Hydros
S7	120	Hydros
S8	125	Hydros
S9	110	Aloe vera mucilage
S10	115	Aloe vera mucilage
S11	120	Aloe vera mucilage
S12	125	Aloe vera mucilage

5.2.4 Data formulation through experimentation

The required data on performance of alternative process condition with respect to 8 evaluation criteria covering physicochemical and process parameters of NCS was elicited through experimental investigations carried out by producing NCS samples at laboratory scale.

Figure 5.11 shows the experimental setup for NCS sample preparation. It consists of a heating pan placed on an induction heater. Two thermocouples and a multi-meter were mounted to the heating pan to sense and record the juice and the pan surface temperature. The whole setup is placed on the mass balance (Kern & Sohn GmbH KB10000-1 make), having a measuring range of 0 to 10 kg and a resolution of 0.1 g, to measure the mass change during the juice clarification and evaporation process. The details of sensors and instruments used in the present experimental analysis with specifications, range, accuracy, and make have been tabulated in the *Table 5.15*. The energy required for boiling the juice is supplied using electrical power. The energy meter is connected to the setup to measure the total energy required to carry out the clarification and evaporation process.

Figure 5.11 Experimental setup for NCS sample preparation

Table 5.15 Details of sensors and instruments used in the present experimental analysis

Sensor/instrument	**Specification**	**Range**	**Accuracy**	**Made**
Thermocouple	K type, Cablelength:1M, Interface Type: flat plug-in, Interface Length: 12.5MM	0-600^{o}C	2.5%/0.75%	ELECTRONICS
Hardness tester	speed of 10 mm/s, test speed of 1 mm/s, post-test speed of 10 mm/s and compression distance of 3mm	Max. force 10kgf	$\underline{+}$0.5g	TA. XT plus texture analyzer
Refractometer	IP65 water resistance 55 x 31 x109 mm, 100g	Brix: 0.0-95% Temp: 9.0-99^{o}C	Brix: $\underline{+}$ 0.2% Temp: $\underline{+}$ 1^{o}C	ATAGO
Mass balance	W×D×H 163×245×79 mm Optional battery operation, 9 V, operating time up to 20 h, Auto-off Permissible ambient temperature 5 °C/35 °C	0-10kg	$\underline{+}$0.1 g	Kern & Sohn GmbH KB10000-1
pH meter	Type: Touch screen Benchtop single-channel. 235 x 188 x 75 mm 1510g	-2 – 20	$\underline{+}$ 0.002	Seven Excellence pH meter S400

The sugarcane juice for experimental investigations was sourced from a sugarcane mill made of wooden rollers located in Shameerpet, a rural town in Hyderabad of Telangana state, India. The sugarcane juice for the preparation of NCS is subjected to a different clarifiant-striking temperature combination.

Initially, pH of the obtained sugarcane juice is first corrected to a range of 6.5-7 by adding 30ml of calcium oxide solution to 1 litre of juice, followed by filtration to remove any suspended impurities. Then the juice was transferred to the boiling pan for further heating, clarification, and concentration of sugarcane juice. As the juice is being heated, the required clarification, concentration of juice and finally the NCS sample preparation was achieved for the above mentioned clarifiant-striking point temperature combinations, as described below:

(i) No clarificants

The pH adjusted sugarcane juice was heated and continued further without the addition of any clarificants until the juice attained the required striking point temperature (i.e., 110°C, 115°C, 120°C & 125°C) and was uniformly cooled by manual stirring.

(ii) *Chemical clarificant*

As the pH adjusted sugarcane juice was heated, 0.8g of hydros was added when the juice temperature reaches 80°C. The scum so formed was removed manually by a strainer. The boiling process was continued until the juice attained the required striking point temperature (i.e., 110°C, 115°C, 120°C & 125°C) and was uniformly cooled by manual stirring.

(iii) *Organic clarificant*

As the pH adjusted sugarcane juice was heated, the Aloe vera mucilage at 0.4% concentration of sugarcane juice was added to the juice during boiling. A total of 4 g of Aloe vera mucilage per 1L of sugarcane juice was added in 2-3 regular intervals. The boiling process was continued until the juice attained the required striking point temperature (i.e., 110°C, 115°C, 120°C & 125°C) and was uniformly cooled by manual stirring. The so produced 12

NCS samples (*Figure 5.12*) under various clarificant- striking temperature combinations were then stored at refrigeration temperature (5°C) for one week for further physicochemical analysis.

Figure 5.12 Twelve NCS samples prepared under various combinations of striking temperature and clarificant process

The physicochemical parameters viz. non-reducing sugar (sucrose), moisture content, hardness, color and taste were measured for the 12 NCS samples, by following the established protocols as described below:

(i) Determination of non-reducing sugar content (Sucrose)

The non-reducing sugar content in the samples was determined according to the manual given by the food safety and standards authority of India (FSSAI. 2016, n.d.; FSSAI. 2015., n.d.), which is originally known as Lane and Eynon method (Lane 1923) . This particular method was used for the following reasons: (a) the method/protocol given is exclusively meant for sugars and sugar products (b) as evinced through the published resources (Sankhla et al. 2011; Rakesh Kumar and Kumar 2021), the same method/protocol has been extensively used for similar assessments.

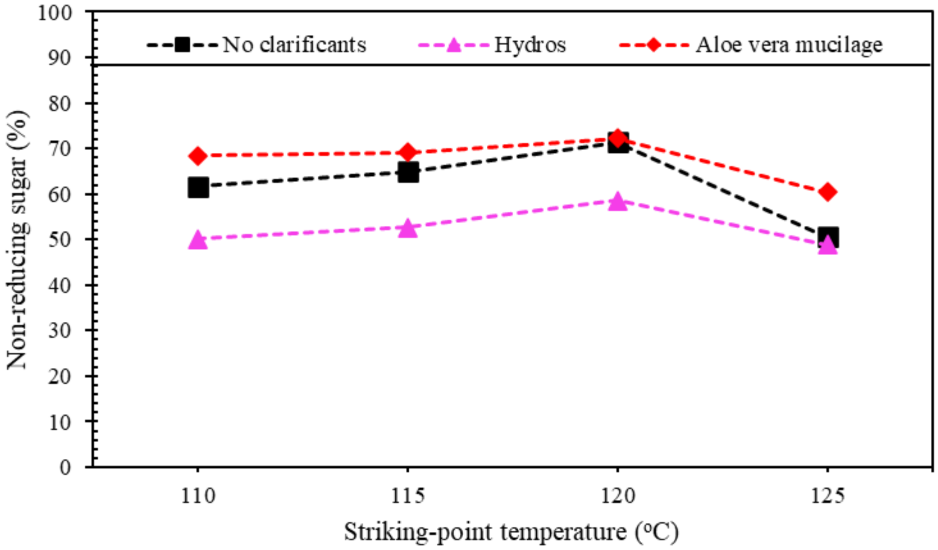


Figure 5.13 non-reducing sugar content of NCS sample at different process conditions

Figure 5.13 presents the non-reducing sugar content (sucrose) of the NCS sample at different process conditions. The results revealed that the minimum non-reducing sugar content of 50.11%, was obtained when NCS was processed at 110°C, especially when treated with inorganic clarificant, hydros. On the other hand, the maximum non-reducing sugar content of 72.23%, was obtained when NCS was processed at 120°C with organic clarificant, Aloe vera mucilage. It was also observed that the non-reducing sugar content was increased with an increase in the striking temperature up to 120°C with respect to all the clarification processes. Also, at 125°C, a low range of non-reducing sugar content was observed with respect to all clarification processes. This may be because of the inversion of sucrose at high temperatures. Therefore, NCS processed with striking temperatures ranging from 110°C-120°C is suggestable for producing NCS with higher non-reducing sugar content. Also, NCS with organic clarificants showed a maximum non-reducing sugar content with respect to all of the striking temperatures compared to other clarification methods. This addition of organic clarificants eliminates the maximum amount of non-sugar impurities and scum removal with higher NCS recovery, thereby maximizing the non-reducing sugar content. Hence, for producing NCS with high non-reducing sugar content, the sugarcane juice may be treated with organic clarificants, especially Aloe vera mucilage and subsequently subjected to heating up to striking temperature in the range of 110°C-120°C. Also, by and large, the obtained results related to nonreducing sugar with the above-mentioned process conditions are in agreement with the ones available in the similar works carried out by G. P. Rao & Singh (2022) & (Patil et al. (1999) (Patil et al. 1999)(G. P. Rao and Singh 2022)

(ii) Determination of moisture content

The moisture content in the NCS samples was determined using a vacuum oven as per the methodology given by FSSAI(FSSAI. 2015., n.d.). Initially, 5g of NCS sample was evenly distributed on the bottom of the dish and was heated in the vacuum oven for two hours at 70°C, while a slow current of air was admitted into the oven during heating. The sample was then cooled and weighed soon after it reached room temperature. This process was repeated until the difference between two successive weights was almost constant. The moisture content of the NCS sample was then determined by equation 2. The same procedure is followed for each NCS sample.

$$Moisture\ content\ (\%) =$$

$$\frac{Weight\ of\ (dish + dried\ sample) in\ g - Weight\ of\ empty\ moisture\ dish\ in\ g}{Weight\ of\ prepared\ sample\ taken\ for\ test\ in\ g} \qquad (2)$$

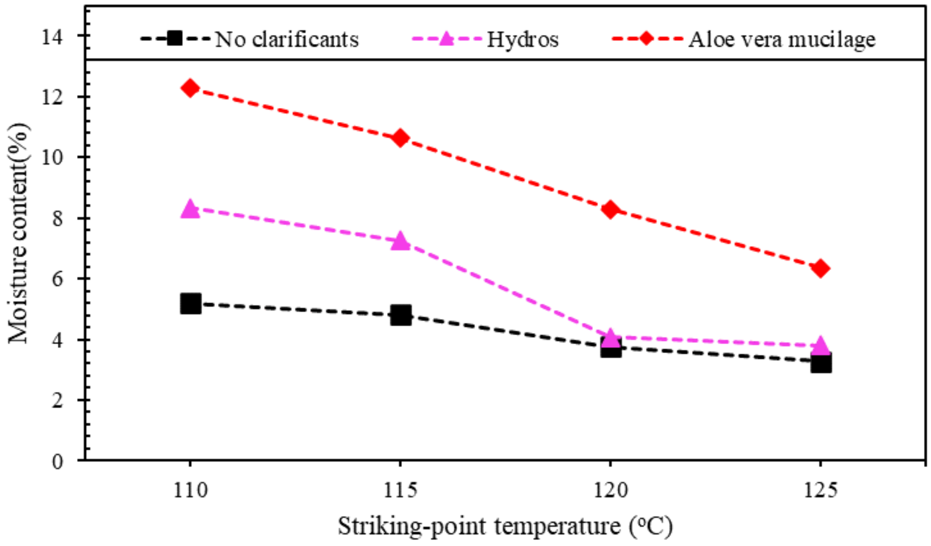


Figure 5.14 Moisture content of NCS sample at different process conditions

Figure 5.14 presents the moisture content of the NCS sample at different process conditions. The results indicate a maximum moisture content of 12.27% when NCS was produced at 110°C with Aloe vera mucilage as clarificant. On the other hand, a minimum moisture content of 3.28%, was observed when NCS was produced at 125°C with no clarificant. It was also observed that the moisture content in the NCS sample was decreased with an increase in striking temperature with respect to all the clarification processes, for the obvious reason of more moisture removal from the juice subjected to higher striking temperatures. Also, the moisture content showed a minimum when NCS is processed without any clarificants with respect to all the striking temperatures compared to organic/inorganic clarificants. Hence, to produce NCS with low moisture content for longer shelf life, the sugarcane juice may be treated without any clarificants and simultaneously subjecting the juice to a higher range of striking temperature.

(iii) Determination of hardness

The hardness of the NCS sample was determined using TA. XT plus texture analyzer (make: stable microsystems), as shown in *Figure 5.15*. A cylindrical probe P/5 (5mm) was used to compress the sample. The mode of measuring the force is compression with a pre-test speed of 10 mm/s, test speed of 1 mm/s, post-test speed of 10 mm/s and compression distance of 3mm. The sample to be examined was placed on a holed plate fastened to the heavy platform and the probe was positioned directly above the plate. Further, the compression process and penetration of the probe onto the sample were measured, and a graph was plotted for the same. For each sample, the hardness was measured three times and the average value of the hardness was taken into consideration. The standard deviation of these values ranges from ±0.002 to ±0.005 with a percentage of error of 0.2%.

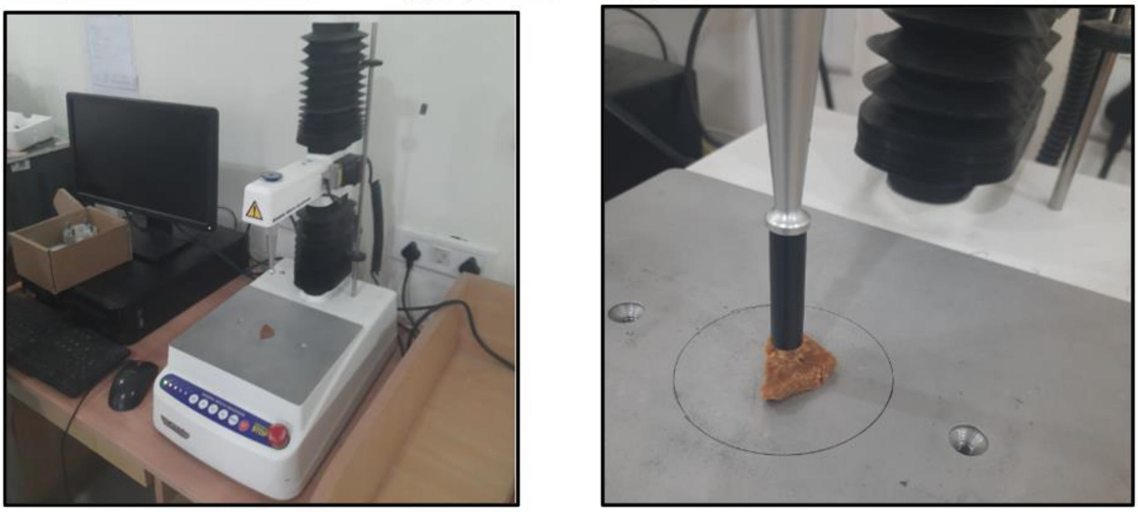


Figure 5.15 Texture analyzer for determining the hardness of NCS samples

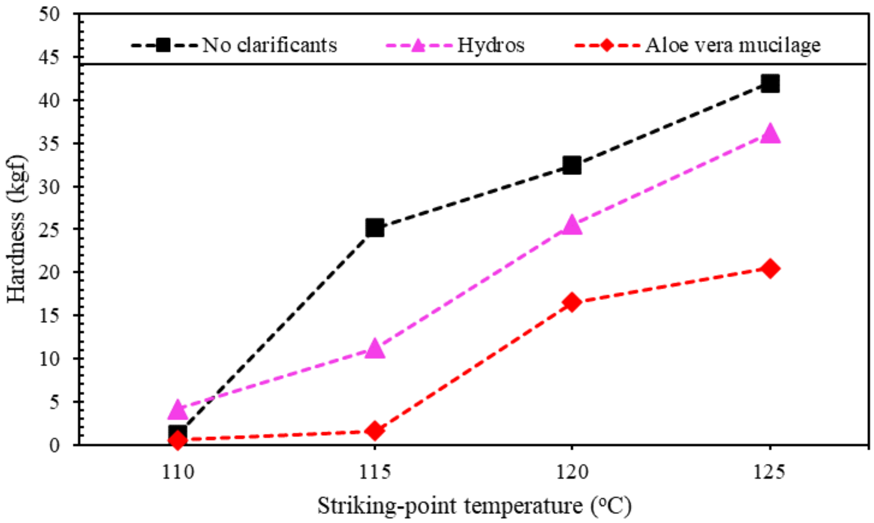


Figure 5.16 Hardness of NCS sample at different process conditions

The hardness values of all samples at different process conditions are shown in *Figure 5.16*. The result revealed that a maximum hardness of 41.94 kgf was found when NCS was produced at 125°C with no clarificants while a minimum hardness of 0.55 kgf was observed when NCS was produced at 110°C with organic clarificant viz. mucilage of Aloe vera mucilage. It was also observed that the hardness of the NCS increased with an increase in the striking temperature with respect to all the clarification processes. This may be because of the higher water removal from the juice resulting in NCS with lower moisture which in turn results in higher crystallinity in the NCS produced.

Also, the hardness was maximum (41.94, 32.42, 25.18 & 1.26 kgf) when NCS was produced with no clarificants for all striking temperatures compared to organic/inorganic clarificants, which may be once again due to the increased crystallinity as a result of higher moisture removal. On the other hand, the hardness showed a minimum (36.20, 25.61, 11.22, 4.19 kgf) when NCS was produced with organic clarificants, i.e., mucilage of Aloe vera mucilage, for all striking temperatures. Hence, to produce quality NCS with higher hardness, the sugarcane juice may be treated without any clarificants and subjecting the juice to a higher range of striking temperature of the order of 115-125°C.

(iv) Measurement and representation of color and taste

The sensory characteristics such as color and taste of the NCS samples were determined by sensory analysis(Chand 2011). A panel of academicians and researchers to evaluate each NCS sample was asked to rate the color and taste of each NCS sample on a scale of 1-5, with 5 being the light golden yellow color and 1 being dark brown for the color attribute. Similarly, 5 was considered to be the most acceptable taste while 1 being the most unacceptable taste. Each sample was tested in triplicate for color and taste and the rounded-off average value was recorded, with a standard deviation of all results ranging from ±0.0011 to ±0.0061.

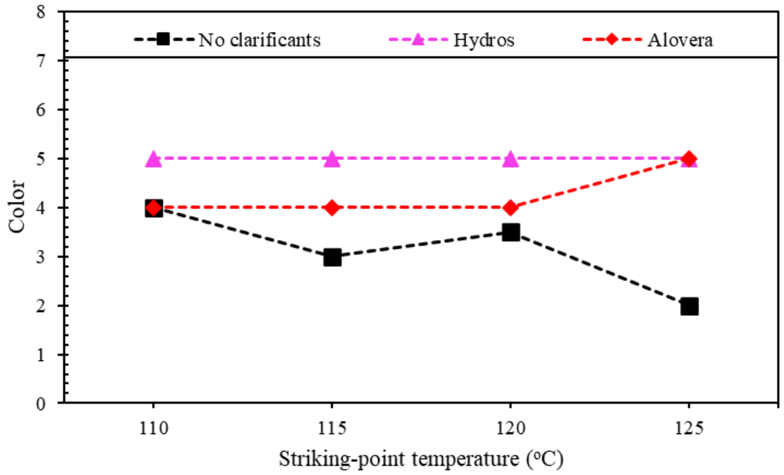


Figure 5.17 Color of NCS sample at different process conditions

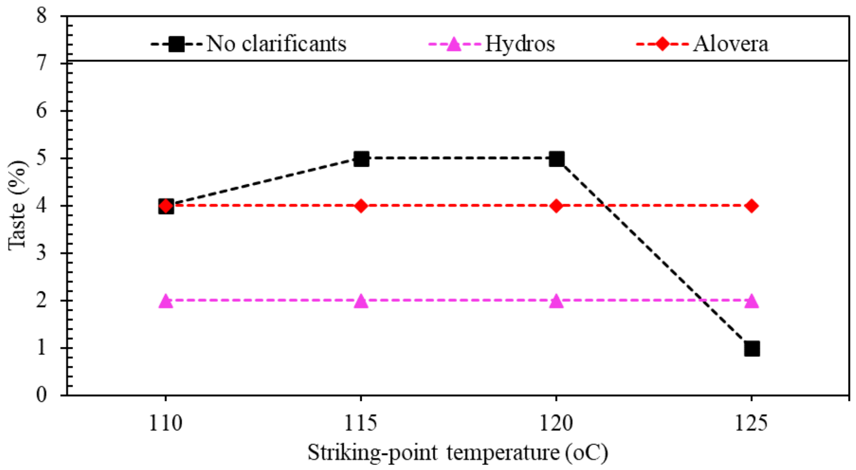


Figure 5.18 Taste of NCS sample at different process conditions

The characteristic values for sensory features of NCS viz. color and taste at different process conditions (obtained based on the adopted scale) are as given in *Figure 5.17* & *Figure 5.18*. A favorable colour of light golden color was observed when NCS was produced with inorganic clarificant (hydros) for all the striking temperatures. A fairly significant increase in the intensity of color was observed when sugarcane was treated with organic clarificant i.e., mucilage of Aloe vera mucilage for all striking temperatures and showed lower color intensity at 125°C striking temperature. The NCS sample showed a significant increase in color when NCS is processed without any clarificants, especially at 125°C striking temperature. This is maybe because the fact that these inorganic clarificants act as a bleaching agent and have a decolorization effect compared to inorganic clarificant. Therefore, sugarcane juice when treated with organic clarifiant (specially hydros), will result in light golden color NCS.

Likewise, the taste of the NCS sample scored better when processed without any clarificants, but at 125°C, the taste was found to be significantly less which may be due to caramelization. The taste of the NCS scored relatively less when produced using mucilage of Aloe vera mucilage as clarificant at all striking temperatures. Also, the taste of NCS produced with inorganic clarificants, i.e., hydros, scored significantly less, which may be due to the addition of chemicals although this addition improves the color intensity.

(v) Production process parameters

The production process parameters such as process time, cost of clarificants, and energy required for producing NCS from one liter of sugarcane juice were measured directly, as the NCS was being produced in the laboratory. The processing time for producing NCS at 110, 115, 120 & 125°C was observed to be 45, 47, 48 & 51 minutes, respectively, with all the clarification processes. The increase in total processing time for NCS with an increase in striking temperatures as the time required for reaching these higher temperatures is higher. The energy required for processing NCS was directly measured using an energy meter attached to the experimental setup and was observed to be 0.7 kWh for producing NCS at 110 & 115 ^{o}C and 0.8 kWh for producing NCS at 120 & 125 ^{o}C. Also, as per the existing market conditions the cost of clarificants including the liming cost was noted to be ₹0.32, ₹2.32, ₹3.32 for producing the NCS from 1 liter of sugar cane juice, using no clarificants, hydros, and mucilage of Aloe vera mucilage, respectively.

The consolidated data matrix of 12 NCS samples for 8 evaluation criteria c covering physicochemical and process parameters of NCS elicited through experimental investigations are tabulated in *Table 5. 15*.

Table 5. 15 Data matrix for producing NCS from 1 L of sugarcane juice subjected to various clarificant-striking temperatures combinations

NCS sample	**Evaluation criteria**							
	C1	**C2**	**C3**	**C4**	**C5**	**C6**	**C7**	**C8**
S1	61.68	5.19	1.26	4	4	45	0.32	0.7
S2	64.85	4.82	25.18	3	5	47	0.32	0.7
S3	71.32	3.76	32.42	3.5	5	48	0.32	0.8
S4	50.53	3.28	41.94	2	1	51	0.32	0.8
S5	50.11	8.33	4.19	5	2	45	2.32	0.7
S6	58.59	7.25	11.22	5	2	47	2.32	0.7
S7	52.75	4.08	25.61	5	2	48	2.32	0.8
S8	48.91	3.80	36.20	5	2	51	2.32	0.8
S9	68.88	12.27	0.55	4	4	45	3.32	0.7
S10	72.23	10.63	1.61	4	4	47	3.32	0.7
S11	69.11	8.29	16.51	4	4	48	3.32	0.8
S12	60.36	6.36	20.49	5	4	51	3.32	0.8

5.2.5 Assessment and selection of appropriate process conditions

The required computations to assess and select an appropriate process condition for producing quality NCS, MCE techniques namely, TOPSIS is considered. The assessment by these MCE techniques require data formulated in the pay-off matrix and the evaluation criteria weights obtained by MCE weight estimation method viz. AHP. The weights obtained by AHP for stakeholder groups are considered to obtain the assessment values by TOPSIS. As per step 1 in the TOPSIS methodology. The weighted normalized matrix was constructed by integrating the normalized data matrix and evaluation criteria weights as per step 2 in the TOPSIS methodology. This was followed by computations of ideal positive and negative solutions as per step 3 in the TOPSIS methodology and then the determination of relative closeness of an alternative as presented in *Table 5*.17. The final ranks of NCS samples are illustrated in *Figure 5.19*.

Table 5.17 Assessment values of each alternative process condition for producing quality NCS using TOPSIS

NCS sample	**Assessment value**
S1	0.555
S2	0.774
S3	0.878
S4	0.498
S5	0.283
S6	0.368
S7	0.496
S8	0.530
S9	0.432
S10	0.466
S11	0.573
S12	0.617

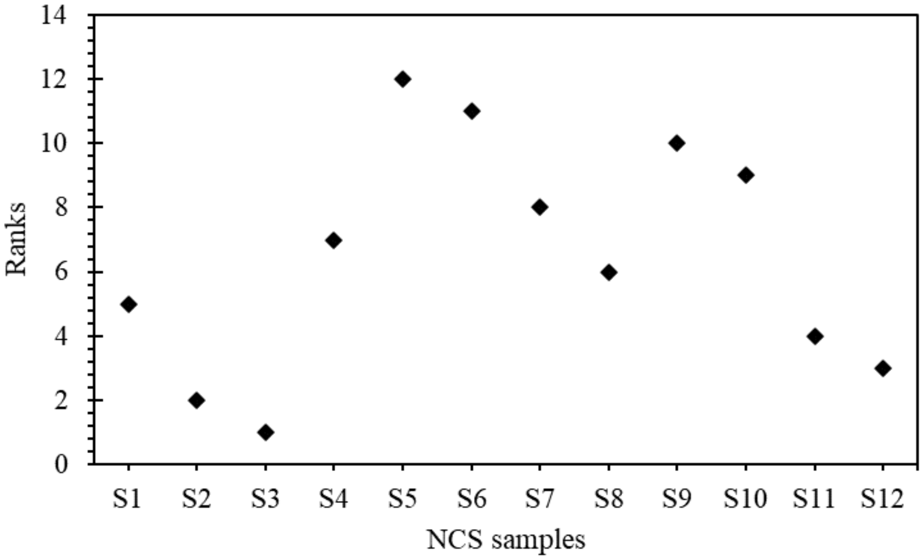


Figure 5.19 Ranking of juice clarification alternative in TOPSIS

As observed from the results given in *Table 5.17* & *Figure 5.19*, NCS samples 2 &3 i.e., the samples produced from sugarcane juice subjected to a striking temperature of 115 and 120°C with no clarificants were best ranked, whereas the sample 1 & 4 i.e., the samples produced from sugarcane juice subjected to striking temperature of 110°C & 125°C, with no clarificants, was comparatively least ranked. It may be due to lower content of non-reducing sugar, unfavorable color, taste and process time. It is also observed that NCS samples 9, 10, 11 & 12 processes under organic clarificant, viz., mucilage of Aloe vera mucilage with respect to all striking temperatures were relatively least ranked though it is good and preferred for human consumption. This may be due to the higher moisture content and low hardness of the NCS sample and the high cost of clarificants. Also, it could be observed that the NCS samples 5, 6, 7 & 8 processed under inorganic clarificant i.e., hydros with all the striking temperatures, were also relatively least ranked due to its lower non-reducing sugar content, unfavorable taste and cost, and its possible inedibility due to the presence of chemicals. This means that, the current practice of using inorganic clarificant, i.e., hydros, is to be avoided and it is advisable to produce NCS without adding any clarificants. This also reduces the production cost to produce NCS of good quality and better one for human consumption. In essence, the undertaken experimental investigations and MCE suggest that sugarcane juice subjected to striking temperatures 115°C and 120°C with no clarificants will produce good quality NCS at low cost.

In essence, following are the conclusions that could be obtained from the undertaken MCE of various juice evaporation technologies and process condition to carry out the evaporation process:

- Criteria weights by AHP and entropy method indicate that the capital cost, followed by heat utilization efficiency and quantity of NCS produced, are the most essential criteria in identifying the sustainable juice evaporation method for production of NCS.
- Modified single pan evaporation unit (with 1.08 as group priority value) was found to be the most sustainable juice evaporation unit for production of NCS.
- The experimental investigations of physiochemical and production process criteria of 12 NCS samples, the undertaken MCE for reveal that sugarcane juice subjected to striking temperatures 115 and 120 °C and without adding any clarificants will produce NCS satisfying all the physiochemical and production process parameters.

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6. MCE of Technologies for NCS Drying Sub-Process

Keywords

NCS drying

Greenhouse drying

Heat pump drying

Open sun drying

Tunnel drying

Moisture beyond 5% in the finally produced NCS makes it conducive for the inversion of sugars, growth of fungus & bacteria, reduced taste & appearance, all contributing to inferior quality of NCS. Drying is the final, yet crucial sub-process which is aimed to remove the excess moisture, so as to improve the shelf-life of NCS before it is taken to subsequent stages in the supply chain. Open sun drying is the current industry norm although there are other effective and sustainable options that may be attempted. This chapter presents the undertaken MCE based works for selecting a suitable and sustainable drying technology for improving the shelf-life and quality of NCS.

6.1. MCE of NCS drying process

Generally, in India, the production of NCS begins in September or October and continues till March /April and the NCS produced goes through the remaining stages of the supply chain and end use during the remaining months of the year(Chand 2011). Field and literature studies undertaken indicate that (a) moisture percentage in the freshly produced NCS ranges from 8% to 15% (Kumar A 2006) (b) moisture levels above 10% in the produced NCS leads to the (i) growth of certain fungus and bacteria (ii) formation of invert sugars (iii) affect the taste and color of NCS, all reducing the edibility of and shelf life of the NCS (Chand 2011)(c) a moisture content of under 5% is preferred for a longer shelf life(Farooque DP. 1954). According to one estimate, the inappropriate and inefficient drying methods adopted in the Indian NCS industry contributes to the loss of more than 10% of NCS worth $0.6 million in

India, every year (SRM 2006) All these make it imperative to adopt a proper process to dry the produced NCS to maintain a moisture content of 5% or below in order to increase the shelf life of NCS while meeting the norms and requirements for food hygiene during packing, shipping, and distribution.

In a typical drying process, heat transmitted to the surface of NCS from the surrounding environment is used for sensible heating of the NCS surface and also for vaporizing the moisture present in the NCS. This vapor is subsequently driven away to obtain NCS with moisture within the required limits. Field and literature studies indicate that open sun drying is the major and common practice in almost all the conventional NCS industries. In this method of drying, NCS after the evaporation process, is exposed directly to solar radiation while it is manually stirred for a longer time. The surface of the NCS is heated by absorbed solar radiation and some part of this heat is used to transfer moisture from the NCS surface to the air around it. While this process is simple and does not require external energy, it comes with several disadvantages such as (i) very less moisture removal, producing NCS with moisture levels much higher than 10%, as the process depends on the atmospheric condition (ii) very slow drying (ii) contributes for dust contamination, growth of microorganisms and insect infestation, making the produced NCS inedible.

As an alternative to overcome the difficulties associated with open sun drying, very few other drying technologies have been attempted. Some of these are solar dryers , control cabinet dryer , Greenhouse dryers (Mat Desa, Mohammad, and Fudholi 2019)etc. However, each of these have their distinguishing features in terms of their suitability for NCS drying. For instance, each one of them differing with each other w.r.t. energy required, initial investments, drying time, suitability for large/small scale operation, amount of moisture removed and etc. All the above impels choosing the right drying technology is a complex problem governed by several mutually conflicting sustainability criteria. As established earlier such problems could be solved by MCE. Presented hereunder are different phases of the MCE undertaken to identify suitable and drying technology. The methodology adopted for the selection of suitable and sustainable drying techniques for NCS production using MCE is shown in *Figure 6.1*.

6.1.1 Identification of evaluation criteria

In view of the sustainability requirements, the criteria to be considered must encompass (a) resources required to carry out the drying (b) environmental impacts in and around the plant (c) techno-economic aspects of drying process (d) process output parameters that designate the efficiency of drying process outcomes. Initially, to identify the appropriate evaluation criteria that govern the above-mentioned four elements of sustainability, questionnaires have been prepared based on the literature sources. The information for the questionnaires has been obtained from the field studies conducted at various prominent NCS cottage industries located in the southern part of India. A detailed list of more than 15 criteria has been initially identified through this study. As per the classical principles of MCE, the identified evaluation criteria must be complete, nonredundant, mutually exclusive, and should be minimum. Accordingly, through brainstorming sessions, some criteria were combined while some were divided in to more than one criteria. For example, the criteria, namely “the direct greenhouse emissions" and “the indirect greenhouse emissions,” were combined together as one criterion, namely “greenhouse emissions”. Likewise, “dryer efficiency,” was defined in terms of two criteria viz. “amount of moisture removed” and “energy required.” This systematic procedure has resulted in a detailed list of 9 performance criteria comprising three elements of sustainability. The 9 identified evaluation criteria, their definitions and nature w.r.t maximization or minimization, etc. are as given in *Table 6.1*.

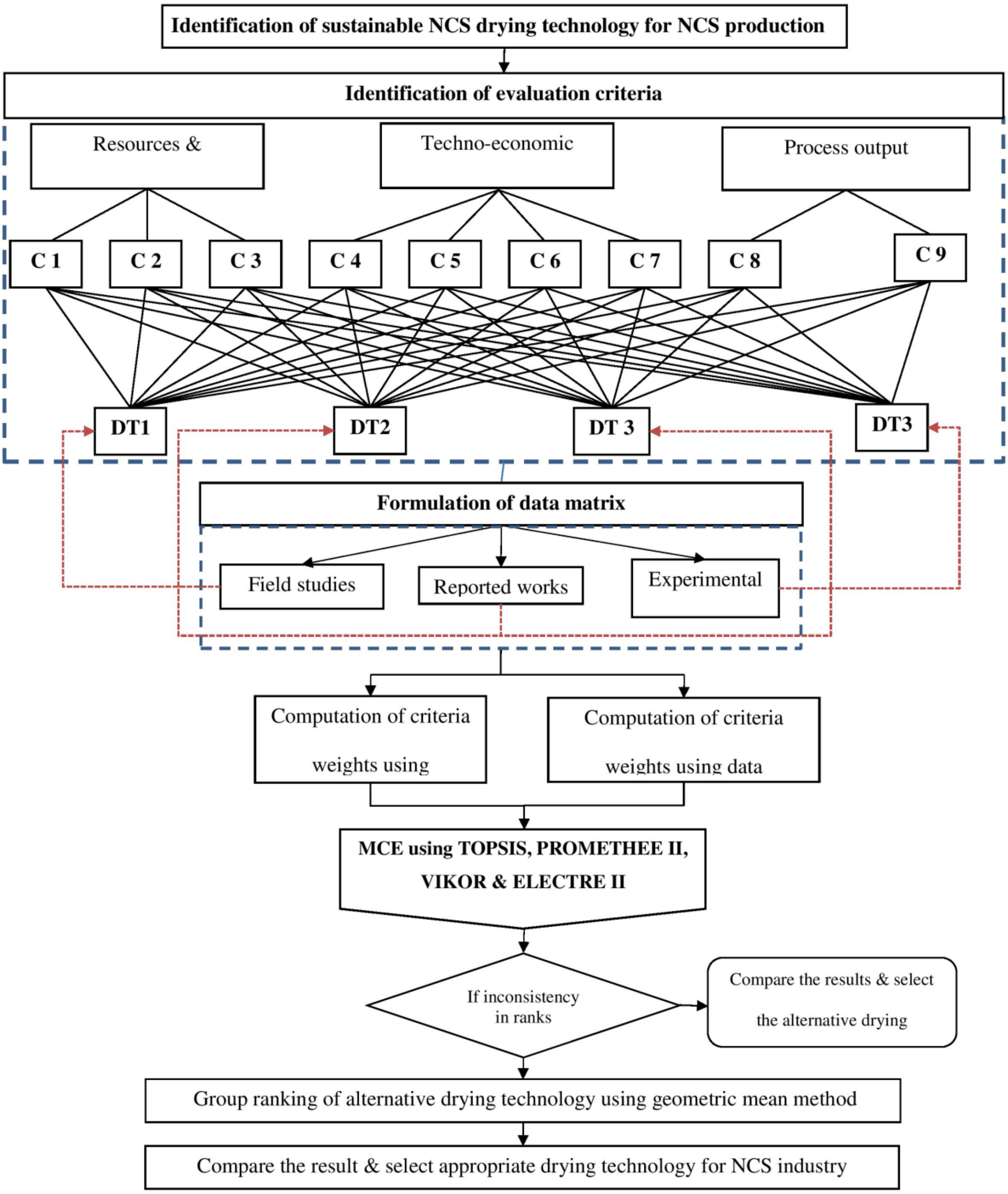

Figure 6. 1 Methodology for selection of sustainable drying technology for NCS industry

Table 6.1 Description of evaluation criteria, with its nature and units for sustainable drying technology for NCS production

Main criteria	Sub Criteria		Definition	Units	Max/ Min
Resources & environmental effect	C_1	Energy required	The total amount of energy required for drying 2kg of NCS to get the desired moisture content.	kWh	Min
	C_2	Greenhouse emissions	The total carbon dioxide equivalent emissions emerged out due to the consumption of energy source	kg of CO_2	Min
Techno-economic	C_3	Effective moisture diffusivity	The rate of moisture movement in 2kg NCS during drying process.	cm^2/s	Max
	C_4	Extent of automation	The degree to which the drying process is automated which is rated on a scale of 1-5, 1 being with less automated and 5 being the greater automation.		Max
	C_5	Capital and maintenance cost	The investment & service cost incurred on dryer and other accessories to remove moisture from the from 2kg of NCS	₹	Min
	C_6	Energy cost	The cost incurred on the energy spent to complete the drying process for 2kg of NCS	₹	Min
Process output parameters	C_7	Amount of moisture removal	The amount of moisture removed from 2kg of NCS during the drying process.	%	Max
	C_8	Quality of NCS produced	Characteristic feature of NCS produced after drying process and is rated on scale of 1-5, 1 being with less quality and 5 being the good quality.		Max
	C_9	Process time	Time taken to remove the excess moisture present and get desired moisture content in 2kg of the NCS	Minutes	Min

6.1.2 Alternative technologies for NCS drying

As detailed earlier, open sun drying is the current NCS industry norm and is being extensively used. The literature and field surveys suggest that the information on alternate drying technologies applicable for NCS is very sparse. Some of the reported alternate drying technologies for NCS drying are green-house drying, tunnel drying.

In order to reduce the shortcoming of the open sun drying for NCS drying, Anil Kumar. (Jain and Tiwari 2004; Tiwari, Kumar, and Prakash 2004; Kumar A 2006) studied and developed a greenhouse dryer for removing the excess moisture content in NCS as shown in *Figure 6.2*. The drying unit is made of PVC pipe and UV film cover and provision of air vent for natural draft. The studies were carried out for drying 2kgs of NCS with 0.03 x 0.03 x0.01 m^3 dimension. NCS produced by this process of drying results in desired moisture content but takes a longer time and depends on the atmospheric condition(Kumar A 2006; Jain and Tiwari 2004; Tiwari, Kumar, and Prakash 2004; Anil Kumar and Tiwari 2006). These dryers are best suited for small scale capacity and require minimal investment cost with no external energy. Similar, S.P. Raj et al. (2020) designed a minimal energy-intensive tunnel dryer to condense moisture content in the granular NCS below 3% as shown in *Figure 6.3* (Raj et al. 2021). Though these types of drying units require large capital investment and maintenance cost but yield a larger production rate.

Accordingly, these 2 and open sun drying had been the natural choices for the present MCE problem. Additionally, a heat pump-based option has also been considered in view of the competing advantages, this option carries.

As the name is suggesting, Heat pump dryer (HPD) (*Figure 6.4*), employs a heat pump system to generate conditioned air to be sent into a dryer system, where the actual drying happens. It is reported that HPD when used for similar applications (Pendyala, Devotta, and Patwardhan 1986; Hossain, Gottschalk, and Hassan 2013; Patel and Kar 2012; By Phani Kumar

Adapa 2001; A. Singh, Sarkar, and Sahoo 2019; Pal and Khan 2008; Salehi 2021) carries following advantageous features:

- controlled drying conditions (temperature and humidity) for higher product quality with little energy demand and best suitable for temperature and humidity sensitive food materials.
- economical compared to other controlled dryers.
- It has a wide range of drying conditions and has a higher specific moisture extraction rate.
- produce better quality products and require less drying time, energy and operation cost compared to other control dryers.

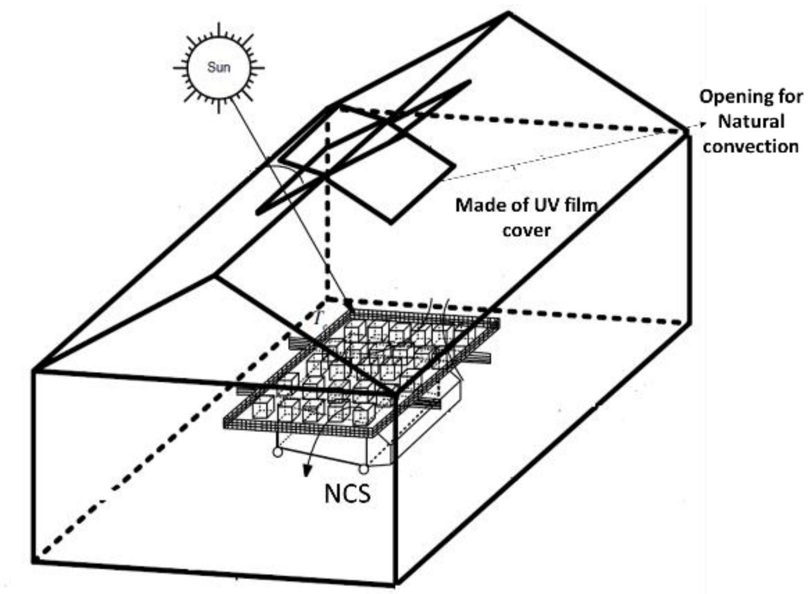

Figure 6. 2 Greenhouse drying of NCS

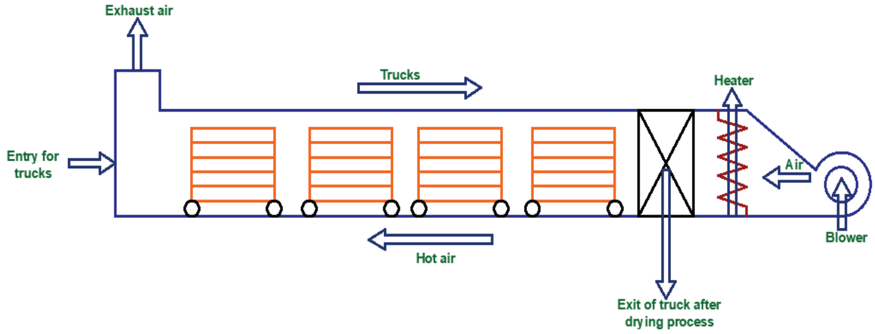

Figure 6.3 Schematic diagram of tunnel dryer for drying NCS

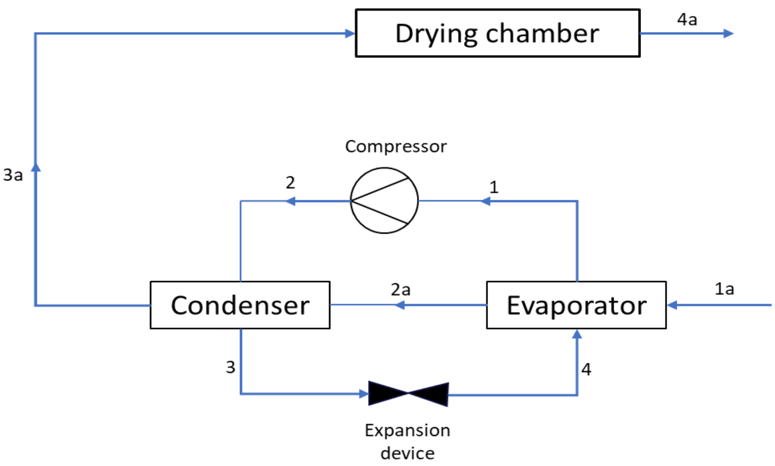

Figure 6.4 Heat pump dryer for drying NCS

6.1.3 Data formulation

Data for the alternative open-sun drying is elicited through field studies conducted during 6–12th March, 2019 at Anakapalle, Andhra Pradesh and the obtained data is substantiated with the published works(Tiwari, Kumar, and Prakash 2004). Similarly, the data for the alternative greenhouse drying and the tunnel drying was taken from the published works(Anil Kumar and Tiwari 2006). Since all the data for greenhouse, open sun drying is available for 2 kg, therefore the data for tunnel dryer is normalized for 2kg.

Also, the data for HPD is obtained for 2kg from the experimental investigations. The NCS for the present investigations is sourced from the NCS production unit, Anakapalle, Andhra Pradesh, India, and the initial moisture content was measured to 12%. To measure the change in mass of the material placed in the tray, a mass balance (Kern & Sohn GmbH KB10000-1) with a measurement range of 0 to 10 kg and a resolution of 0.1 g is coupled to the drying chamber. The drying chamber is also equipped with temperature and humidity controlling and measuring sensors. The atmospheric air is made to pass through the heat pump to get the required temperature and humidity and is passed through the drying chamber for removing the excess moisture present in the NCS. The process in HPD consists of two working loops viz. refrigeration and air loop. *Figure 6.5* illustrates the refrigeration and psychrometric cycle involved in the HPD for drying NCS. The atmospheric air entering the evaporator of the heat pump at state point 1a is cooled to below dew point temperature and is dehumidified. This low temperature and dehumidified air enters the condenser at state point 2a and is heated sensibly to get the required drying condition to remove the moisture present in NCS. Then the air at the required condition achieved by the heat pump enters the drying chamber at state point 3a and removes the moisture present in the NCS and leaves the chamber at state point 4a. The moisture content in the NCS sample is calculated by weighing the sample for every 20s. The drying process is stopped when the sample reaches the desired moisture content. Also, the required data for each criterion viz. energy required, process time etc. for HPD for MCE assessment are measured, noted and determined during the experimental investigations. The consolidated data matrix of 4 NCS drying technologies for 9 evaluation criteria to produce the required quality for drying 2kg of NCS through the drying process is given in *Table 6.2*.

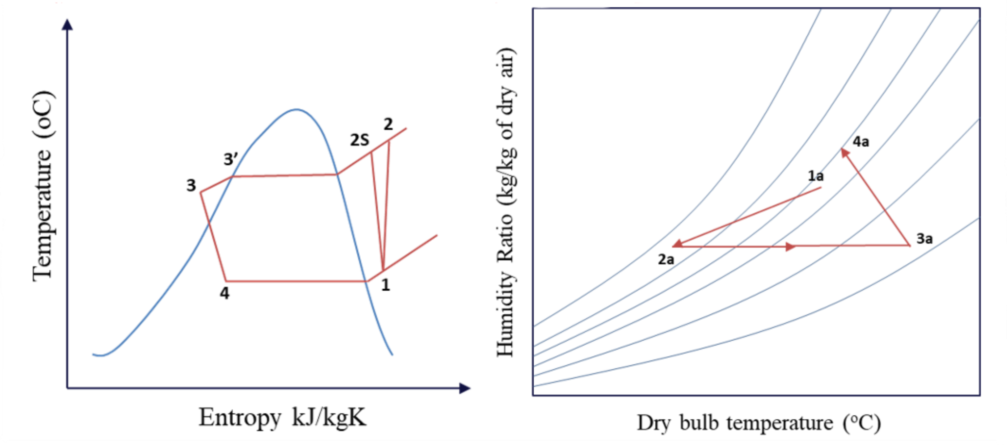

Figure 6.5 Refrigeration and psychrometric cycle involved in the HPD for drying NCS

Table 6.2 Data matrix for alternative drying technology for NCS drying

Alternatives	Sub-criteria								
	C_1	C_2	C_3	C_4	C_5	C_6	C_7	C_8	C_9
DT_1	0	0	0.403	0	0	100	0.1	0	90
DT_2	1.978	794.53	0.02028	2	0	900	6.35	1	1800
DT_3	0.15	33955.2	0.02839	4	0.6	100000	1.75	4	68
DT_4	0.81	1700	2.7	4	3.25	45390	7	4	30

6.1.4 Computation of evaluation criteria weights

For the present MCE of identifying the sustainable drying technology for NCS production, well-established and commonly used MCE technique viz. AHP and entropy methods are considered for determining the weights of evaluation criteria. AHP determines the subjective weights that rely on the inputs of the stakeholders while the entropy methods compute the object weights that depend on the actual data formulated in the data matrix. To ensure accuracy and to prevent any devaluation of the weights assigned to the evaluation criteria that determine the final assessment of alternatives and to reflect outcomes in a fashion that is more logical and scientific, both AHP and entropy methods are considered.

As per AHP methodology, each criterion was compared with others using Saaty's nine-point scale of relative importance, to form a pairwise comparison matrix. The data for generating this pairwise comparison matrix was obtained from a panel of experts comprising of researchers and academics working in the relevant areas, NCS producers and end users, through personal interviews, questionnaire-based surveys and brainstorming exercises which happened during the period from 2nd to 18th March 2020. The criteria weights were then computed by following the established process. As required by the AHP methodology, the computed criteria weights were checked for their consistency by computing consistency ratio (CR). In the cases, when the CR was greater than 0.1, the panel was re-consulted, fresh data was obtained, pairwise comparison matrix was re-formed, weights were re-computed and the CR was re-checked and the process was repeated till the satisfactory results were obtained.

The determination of objective weights by the entropy method is based on information theory, in which the criteria weights are derived objectively from the data matrix. The significant benefit of this approach is its objectivity. The assessment of alternative NCS drying technology is based on a given 9 criterion that decides its relative significance without direct interference of the considered stakeholder groups.

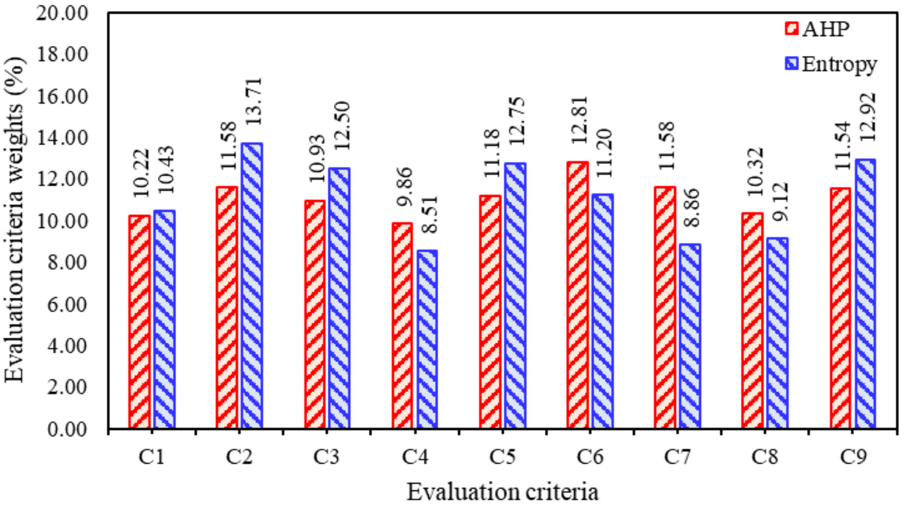

Figure 6.6 Weights of evaluation criteria for selection sustainable drying technology for NCS production

Figure 6.6 indicates the weights of 9 evaluation criteria with respect to AHP and entropy methods. It is observed that capital cost, energy cost, process time and greenhouse emissions are the most essential criterion in selection of appropriate drying technology with respect to stakeholder group opinion and the data present in data matrix. On the other hand, the extent of automation is given least weighted criteria in assessing the appropriate drying technology for NCS with respect to both stakeholder group opinion and the statistical data present in data matrix. Also, the amount of moisture removed is also observed be least weighted criterion with respect to the statistical data. Its is also observed from the computed AHP and entropy weights that considered stakeholders opinion are more or less the same in relation to the statistical data. Furthermore, the degree of consistency for the priorities given by the decision-makers is measured to be 0.034 respectively (CR < 0.1), indicating that weights obtained by the decision-makers are considered for further assessment along with the objective weights.

6.1.5 Assessment and selection of alternative technology for NCS drying

The required computations to assess and select a sustainable drying technology for NCS production, four MCE techniques namely TOPSIS, PROMETHEE II, VIKOR & ELECTRE I were considered. The assessment by these MCE techniques require data formulated in the payoff matrix and the evaluation criteria weights obtained by two MCE weight estimation methods viz. AHP & entropy method. The weights obtained by AHP for stakeholder groups & entropy weights statistical data are considered to obtain the assessment values by TOPSIS, PROMETHEE II, VIKOR & ELECTRE I.

Table 6. 3 Assessment values of alternative drying technologies for NCS production in TOPSIS

Alternatives	AHP weights	Entropy weights
	CC_j^*	CC_j^*
DT_1	0.609	0.638
DT_2	0.525	0.514
DT_3	0.484	0.484
DT_4	0.656	0.647

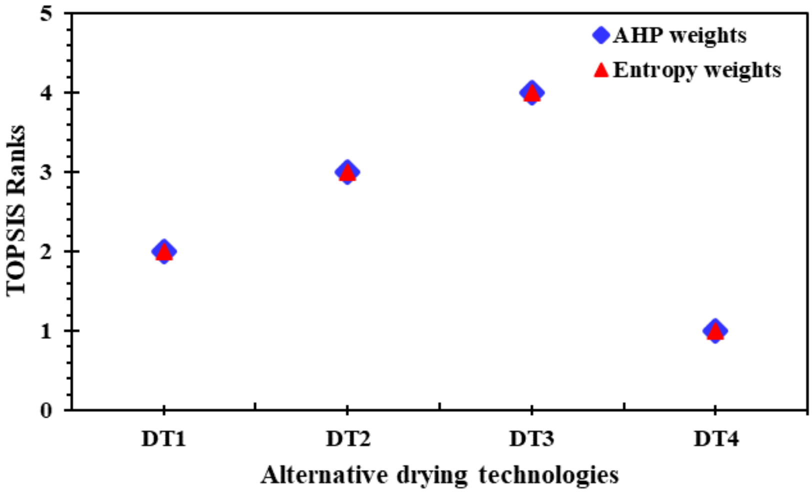

Figure 6.7 Ranking of alternative dying technology for NCS production in TOPSIS

Table 6. 3 presents the assessment values of each alternative drying technology by TOPSIS with respect to AHP and entropy weights. The ranking of alternative drying technology is given according to this methodology and is illustrated in *Figure 6.7*. It is observed that drying technology DT_4 that is heat pump dryer is observed to be best preferred alternative for drying NCS with respect AHP and entropy weights. This may be due higher amount of

moisture removal in relatively with less process time. Also, the alternative $DT_{1,}$ the current practice that is open sun drying next best ranked alternative with respect to both AHP and entropy weights. The remaining two alternatives DT_2 & DT_3 are comparatively less preferred for drying NCS to get the required moisture content in NCS. It may be because of high investment cost and low moisture removal with high process time.

Table 6.4 Assessment values of alternative drying technologies for NCS production in PROMETHEE II

Alternatives	AHP weights	Entropy weights
	Ø	Ø
DT_1	0.095	0.117
DT_2	-0.011	-0.035
DT_3	-0.168	-0.164
DT_4	0.085	0.082

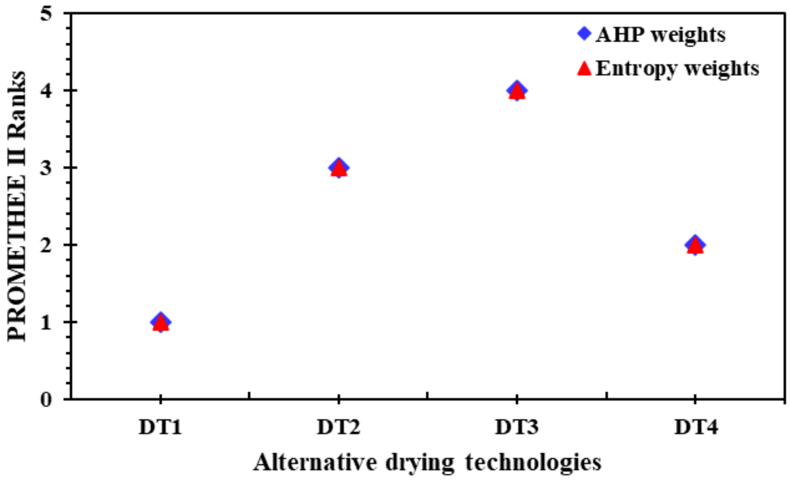

Figure 6.8 Ranking of alternative drying technologies for NCS production in PROMETHEE II

Table 6.4 presents the assessment values of each alternative drying technology by PROMETHEE II with respect to AHP and entropy weights. The ranking of alternative drying technology is given according to this methodology and is illustrated in *Figure 6.8* . It is observed that drying technology DT_1 that is current practice of drying CS i.e., open sun drying is observed to be best preferred alternative for drying NCS with respect to AHP and entropy weights. This may be due lower capital investment with zero energy requirement and energy cost with no greenhouse emissions. Similarly, the alternative DT_4, Heat pump dryer is observed to be the next best ranked alternative with respect to both AHP and entropy weights. It may be because of higher amount of moisture removal in relatively with less process time. The remaining two alternatives DT_2 & DT_3 are comparatively less preferred for drying NCS to get the required moisture content in NCS. It may be because of high investment cost and low moisture removal with high process time.

Table 6. 5 Assessment values of alternative drying technologies for drying NCS in VIKOR

Alternatives	AHP weights	Entropy weights
	Q	Q
DT_1	0.511	0.290
DT_2	0.606	0.868
DT_3	1.000	0.985
DT_4	0.000	0.340

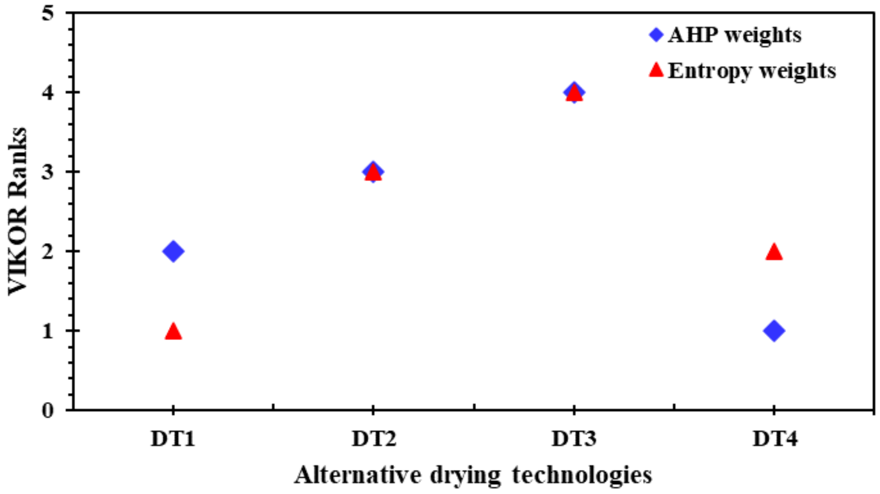

Figure 6.9 Ranking of alternative NCS drying technology in VIKOR

Table 6. 5 presents the assessment values of each alternative drying technology by VIKOR with respect to AHP and entropy weights. The ranking of alternative drying technology is given according to this methodology and is illustrated in *Figure 6.9*. It is observed that drying

technology DT_1 that is open sun drying is ranked 1st with respect entropy weights and ranked 2nd with respect to AHP weights. Similarly, drying technology DT_4 that is Heat pump dryer is ranked 1st with respect AHP weights and ranked 2nd with respect to entropy weights. This may be, according to the stakeholder preference with their practical experience heat pump dryer may be best suitable for drying NCS while, according to the statistical data present in the data implies that open sun is best preferred drying technology. The remaining two alternatives DT_2 & DT_3 are comparatively less preferred for drying NCS to get the required moisture content in NCS. It may be because of high investment cost and low moisture removal with high process time.

Table 6.6 *Net superior (C_a) & net inferior (D_a) values of alternatives*

Alternatives	AHP weights		Entropy weights	
	Ca	Da	Ca	Da
DT_1	0.076	0.041	0.129	-0.020
DT_2	-0.150	0.077	-0.165	0.077
DT_3	-0.112	0.075	-0.126	0.077
DT_4	0.186	-0.236	0.161	-0.216

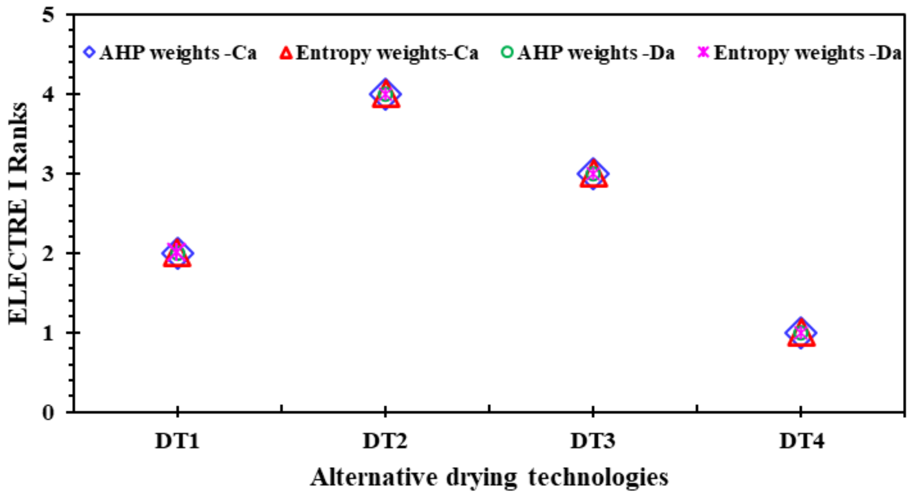

Figure 6.10 Ranking of alternative drying technologies for NCS production in ELECTRE I

Table 6.6 presents the assessment values of each alternative drying technology by ELECTRE I with respect to AHP and entropy weights. The ranking of alternative drying technology is given according to this methodology and is illustrated in *Figure 6.10*. It is observed that drying technology DT_4 that is heat pump dryer is observed to be best preferred alternative for drying NCS with respect AHP and entropy weights for both net superior (C_a) & net inferior (D_a). This may be due higher amount of moisture removal in relatively with less process time. Also, the alternative DT_1, the current practice that is open sun drying next best ranked alternative with respect to both AHP and entropy weights net superior (C_a) & net inferior (D_a). The remaining two alternatives DT_2 & DT_3 are comparatively less preferred for drying NCS to get the required moisture content in NCS. It may be because of high investment cost and low moisture removal with high process time.

The outcomes of the above MCE evaluation imply that there has been an inconsistency in the ranks of alternative NCS drying technologies. This inconsistency in each NCS drying technology ranks may be due to the different criteria weights and methodology of four MCE methods can be analyzed by computing the “group decision by the geometric mean method.” *Table 6. 7* & *Figure 6.11* presents the group decision values of alternative drying technology and associated ranks.

Table 6. 7 Group decision values of alternative drying technology for NCS industry

Alternatives	Group decision value
DT_1	1.542
DT_2	3.224
DT_3	3.722
DT_4	1.297

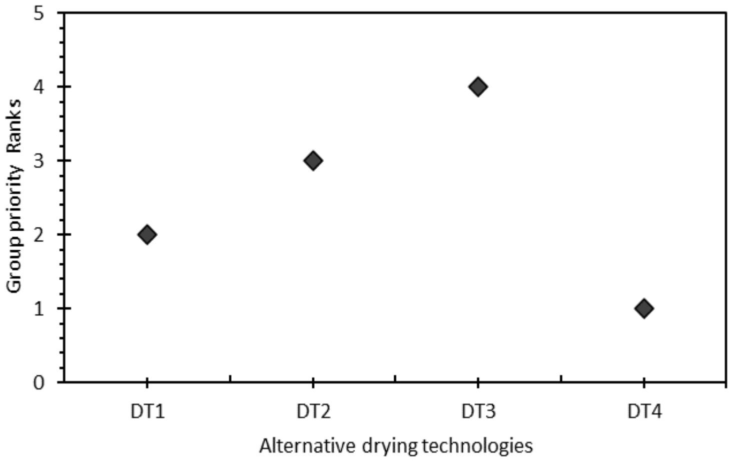

Figure 6.11 Group ranking of alternatives based on MCE techniques

From the *Figure 6.11*, it is observed that drying technology DT_4 that is heat pump dryer is observed to be best preferred alternative for drying NCS with respect AHP and entropy weights. This may be due higher amount of moisture removal in relatively with less process time. Also, the alternative DT_1, the current practice that is open sun drying, is the next best ranked alternative with respect to both AHP and entropy weights. The remaining two alternatives DT_2 & DT_3 are comparatively less preferred for drying NCS to get the required moisture content in NCS. It may be because of high investment cost and low moisture removal with high process time.

In essence, following are the conclusions that could be obtained from the undertaken MCE of various drying techniques:

- Criteria weights computed using AHP and entropy methods indicate that capital cost, energy cost and greenhouse emissions are among the important criteria in identifying the suitable NCS drying techniques for NCS production.
- Among the considered four drying technologies, heat pump dryer (HPD) is the best drying technology for drying NCS to get the desired moisture content and to increase the shelf life of NCS during storing. The current practice that is open sun drying is the next best drying technology for drying NCS.

- The type of refrigerant used is one the most essential component in HPD system which influence the drying condition. Therefore, choosing the right refrigerant for HPD is essential for both product quality and safety concerns, which depends on techno-economic and environmental parameters. The methodology adopted and the complete analysis for identifying the appropriate and sustainable refrigerant based HPD for drying NCS using MCE is illustrated in Appendix III.

7. Summary and Conclusions

Keywords

Non-centrifugal sugar

Multi-criteria evaluation

Agro-based cottage industry

NCS industry is one of the oldest agro-based small-scale cottage industries in India, operated and manned by local farmers. Over the decades, the NCS production processes are crude, energy inefficient, and technically unchanged, which resulted in the continual downfall of the NCS industry. This chapter summarizes the research works undertaken, the conclusion that are drawn out and the solutions for the sustenance of this once well-established NCS industry. Also included in this chapter is the scope for further research in this direction.

7.1. Summary

Non-centrifugal sugar (NCS, also known as Jaggery) industry is undergoing a continual downfall due to crude, energy inefficient, and technically unchanged technologies being adopted in the 4 main sub-processes of NCS production viz. juice extraction, juice clarification, juice evaporation and NCS drying. As one of the pathways to sustain this NCS industry, the research works presented in this thesis were initiated with the objective of bringing out multi-criteria evaluation based solutions to identify the best technological options for the 4 main sub-processes of NCS production, w.r.t. techno-economics, resource utilization, environmental impacts and process output parameters. Extensive field and literature studies have been conducted to finalize (a) the criteria covering the aforementioned parameters (b) alternative technologies for each of the sub-process (c) the applicable MCE tools, that are suitable for the present research problem. The weights of identified criteria for each sub-process covering techno-economics, resource utilization, environmental impacts and process output parameters are computed using applicable MCE-weight estimation methods viz. AHP, FAHP and Shannon entropy. The identified alternative technologies for each sub-process are evaluated using applicable MCE-aggregation methods viz. TOPSIS, PROMETHEE II, VIKOR and ELECTRE I. The required data for the MCE is sourced from extensive field, literature and experimental investigations as applicable. In a consolidated fashion, the undertaken research work indicates that the NCS production line comprising of (a) single horizontal crusher with no usage of water, (b) no clarificants (c) a single pan evaporation unit with a modified furnace design (d) heat pump dryer is the most appropriate process line for the sustenance of the NCS industry. The following sections describe the specific and detail conclusions that could be drawn out of the undertaken research works documented in this thesis.

7.2 Conclusions: MCE on juice extraction and clarifications processes

The undertaken MCE on 6 juice extraction technologies w.r.t. 11 evaluation criteria result in the following specific conclusions:

- Criteria weights computed indicate that capital cost, energy costs, quantity of juice, and man-hours are the most important and influential criteria in identifying the suitable juice extraction techniques for the sustenance of NCS industry.
- “Crusher with a single horizontal roller that uses an electrical motor without any usage of hot water” is found to be the most suitable juice extraction method for the sustenance of the NCS industry.

The detailed conclusion related to juice extraction technologies are as follows:

- The crusher that uses shredders was found to be an inferior option for NCS production with 6 group priority value, although this alternative is being used in the upcoming NCS plants such as the one at Erode. This may be because of high capital and maintenance cost.
- With a group priority value of 1.38, crusher with a single horizontal roller that uses electrical motor without any usage of hot water, was found to be the most suitable and

sustainable juice extraction technique. Although this method of juice extraction extracts relatively small amount of juice, it satisfies all the criteria covering techno-economics, resource utilization, environmental impacts and process output parameters.

- With group priority values of 2.47, multiple roller crushers with hot water usage, regularly used in the sugar industry, could be used as second-best alternative. One of the possible reasons for this alternative as a secondary option is due its high capital cost and CO_2 equivalent emissions.
- With the group priority values of 3.33 and 3.39, the current crushing options viz. “single vertical roller machine that runs on electrical energy without the usage of hot water “and “single horizontal roller machine that runs on diesel engine without the usage of hot water” were found to be inferior option. It may be due to high crushing time, man-hours and energy required. Hence both the options can be dispersed away with, for the sustenance of NCS industry.

MCE of appropriate juice clarification technology was based on 11 evaluation criteria among 5 alternatives. The specific conclusions are as follows:

- Criteria weights computed indicate that initial investment and extent of organic clarifiers are the most important criteria in identifying the suitable method of clarification for improving the quality and shelf-life of NCS using FAHP.
- Clarification with plant mucilage is the most suitable and sustainable method for producing quality NCS.

The detailed conclusion related to juice clarification technologies are as follows:

- Clarification with plant mucilage is the most suitable and sustainable method of clarification for NCS production with assessment values of 0.62 & 0.024 in TOPSIS

& AHP, respectively. It may be due to low initial investments and mainly replacing the chemical that are dangerous to the human consumption

- On the other hand, the present practice of using chemical clarifiers is a relatively an inferior alternative for NCS production with the assessment values of 0.51 & 0.013 in TOPSIS & AHP, respectively. This method of clarification can be used as a secondary option by following the food standard requirements.
- Clarification with membrane technology, installed in few of sugar industries in Hawaii and South Africa, was emerged out to be the least preferred for NCS production, due to its high initial investment and high requirement of energy. Other main problem with this technology is that the membrane gets fouled which need to cleaned periodically.
- Clarification with electrocoagulation and centrifuge process with activated carbon are not preferred options for clarification of sugarcane juice in NCS production, may be due to their high investment cost and high use of energy.

7.3. Conclusions: MCE of technologies for juice evaporation sub-process

The undertaken MCE on 10 juice evaporation technologies w.r.t. 11 evaluation criteria result in the following specific conclusions for the sustenance of NCS industry:

- Criteria weights by AHP and entropy method indicate that the capital cost, followed by heat utilization efficiency and quantity of NCS produced, are the most essential criteria in identifying the sustainable juice evaporation method for the production of NCS.
- “Single pan with the improved furnace” was found to be the most suitable technology for juice evaporation process.

The detailed conclusion related to juice evaporation technologies are as follows:

- The option of “single pan with an improved furnace” was found to be the most sustainable juice evaporation unit for the production of NCS with group priority value of 1.08. It is so, because this evaporation technology satisfies all the criteria covering techno-economics, resource utilization, environmental impacts and process output parameters.

- The traditional single pan evaporation unit, is found to be the second-best alternative for producing NCS with group priority value 1.93. This may be due to the high thermal efficiency of the unit, low capital cost, and low greenhouse emissions and can be used as an alternative for single pan with an improved furnace.
- Evaporation of juice by traditional two pan and four pan units are ranked 9th and 10th with group priority value of 7.66 & 8.22, respectively. This is due to its high capital and energy cost, low thermal efficiency, though having high production rate. With these, these alternatives are the least promising technologies, and hence to be dispensed away with for the sustenance of NCS industry.
- Traditional single pan integrated with solar collector, is ranked 3rd with group priority value 3.34 and comparatively less preferred because of the low production rate and complexity in design.
- Another current alternative, the modified two pan unit, was ranked to be 4th rank with a group priority value of 5.01, which is due to high capital cost and design complexity. Hence this is to be dispensed away with.
- The traditional and modified three pan evaporation units, are less preferred alternatives with 6th & 5th ranks and group priority value of 5.94 & 5.12, respectively. This may be due to its low heat utilization efficiency and high man-hours required for the production of NCS. Hence these are also not the good options for juice evaporation for the sustenance of NCS industry.
- Modified four pan evaporation unit and multi-effect evaporation unit are least preferred with 8th & 7th ranks and group priority value of 7.11 & 6.69, respectively.

This is due to high capital cost and material requirement with complex design, although having high heat utilization efficiency and production rate. Hence these are also not the good options for juice evaporation for the sustenance of NCS industry.

Experimental investigations and subsequent MCE carried out on 12 samples produced in the lab with three clarification methods and striking temperatures ranging from 110 to 125 °C, result in the following specific conclusions:

- Among the 9 physicochemical parameters that govern the quality of NCS, non-reducing sugars and moisture content are the most influential criteria to identify the appropriate process conditions.
- the striking temperatures of 115 °C and 120 °C with no clarificants is the appropriate process condition for producing good quality NCS.

The detailed conclusion related to suitable process conditions for producing quality NCS are:

- Different physicochemical parameters for the 12 samples through experimental investigations range as per the following details: non-reducing sugars (%) 50.11–72.23; moisture content (%): 3.28–12.27; Hardness (kgf): 0.55–41.94; process time from 45 to 51 min.
- NCS produced under inorganic clarificants, i.e., hydros with the lower striking temperature result in low reducing sugar content. NCS produced with no clarificants and subjected to higher striking temperatures result in low moisture content and higher hardness.
- The color intensity of the NCS sample is less when sugarcane juice is treated with inorganic/ organic clarification and resulted in an unfavorable taste. While the color intensity of NCS processed without any clarificants showed a significant increase in color but resulted in good taste except with the 125^{o}C striking temperature.

- The processing time for producing NCS at 110, 115, 120 & 125°C was observed to be 45, 47, 48 & 51 minutes, respectively, with all the clarification process.
- The energy required for processing NCS was observed to be 0.7 kWhr for processing NCS at 110 & 115 °C and 0.8 kWhr for processing NCS at 120 & 125 °C.
- The cost of clarificants was found to be ₹ 0.32, ₹ 2.32 & ₹ 3.32 for processing NCS with no clarificants, hydros, and mucilage of aloe vera, respectively.
- Based on the experimental investigations and the undertaken AHP integrated TOPSIS based MCE suggest that sugarcane juice subjected to striking temperatures 115 and 120 °C and without adding any clarificants is the appropriate process condition for producing good quality NCS.

7.4. Conclusions: MCE of technologies for NCS drying sub-process

The undertaken MCE on 4 drying technologies w.r.t.9 evaluation criteria result in the following specific conclusions for the sustenance of NCS industry:

- Criteria weights computed using AHP and entropy methods indicate that capital cost, energy cost and greenhouse emissions the important criteria for the assessment of the suitable NCS drying techniques for NCS production.
- Heat pump dryer is the most suitable drying technology to get the desired moisture content (of less than 5%) and to increase the shelf life of NCS during storing.

The detailed conclusion related to NCS drying technologies are:

- Heat pump dryer is observed to be best preferred alternative for drying NCS with the group priority value of 1.29. This is due to higher amount of moisture removal in relatively with less process time and hence, can used for drying NCS to get the desired moisture content and to increase the shelf life of NCS during storing.
- The current practice of open sun drying, is the next best preferred alternative with group priority value 3.22. Although, this method of drying requires less energy with

low capital cost, it contributes for dust contamination, growth of microorganisms and insect infestation, making the produced NCS inedible. All these along with higher process time, make this method to be an inferior option for producing quality NCS.

- Greenhouse drying and tunnel drying are comparatively less preferred for drying NCS to get the required moisture content in NCS with group priority values 3.22 & 3.72, respectively. It is because of high investment cost and low moisture removal with high process time.

7.5. Overall conclusion

Consolidating all the above findings and discussions, a sustainable NCS production process line was identified in terms of techno-economics, resource utilization, environmental impacts, and process output parameters using one of the scientific and logical methods viz. MCE. Figure 7. 1 presents the identified sustainable NCS production process line.

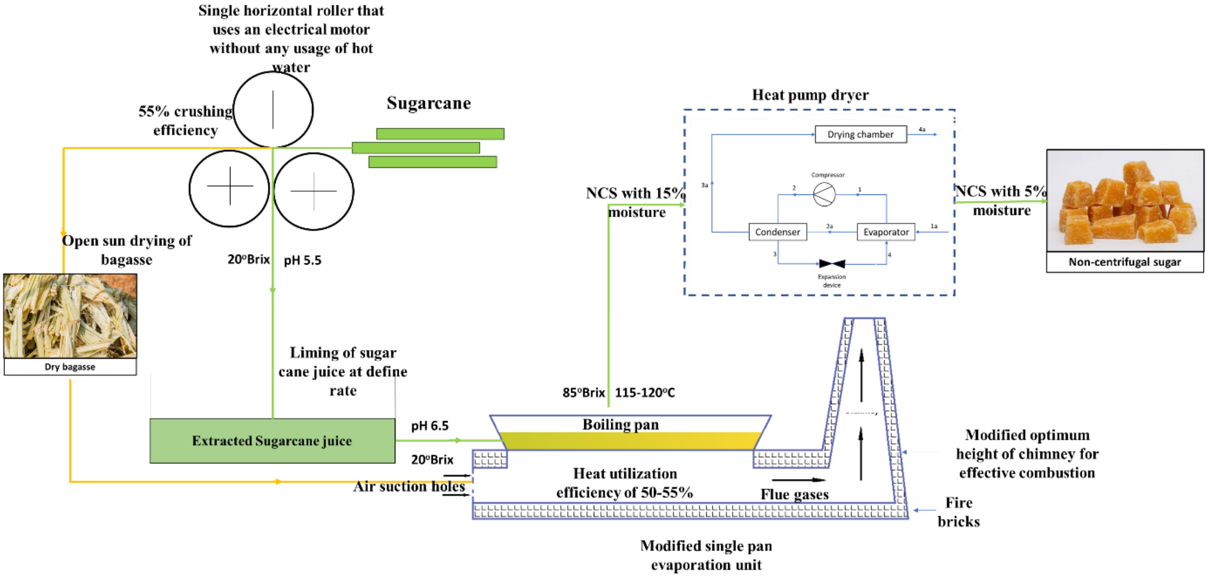

Figure 7. 1 Identified sustainable NCS production process line

Specific Contributions

NCS industry is one of the oldest agro-based small-scale cottage industries in India, whose production and consumption has been undergoing a continuous decline, despite a host of benefits of NCS. In order to revive this once very well-established rural cottage industry, the research works presented in this thesis were aimed to bring out MCE based solutions for the sustenance of NCS industry. The following are the specific contributions of this work:

- The undertaken field and literature studies identified different criteria covering techno-economic, environmental impacts and resource utilizations aspects of NCS production, that influence the sustenance of NCS Industry. It also identified different possible technologies for different sub-processes being followed for NCS production.
- Through the developed MCE models and undertaken analyses, it has been identified that the process line comprising of (a) single horizontal crusher with no usage of water, (b) no clarificants (c) a single pan evaporation unit with a modified furnace design (d) heat pump dryer, is the most appropriate process line for the sustenance of NCS industry.
- The undertaken experimental investigations and subsequent multi-criteria based evaluations identified the most optimum process conditions for producing quality NCS, thereby contributing for the sustenance of NCS industry.
- The research works carried out and presented in this thesis formed a basis for evaluating the existing technologies for each sub-process of NCS production. Using this as the basis, the new technologies emerging out of the future research studies could also be evaluated to assess their contribution for the sustenance of NCS industry.
- The methodology carried out demonstrated the successful use of MCE to bring out solutions for the sustenance of rural cottage industries, which can be extended to other similar industries.

Further Scope of Work

Following are some of the new dimensions to extend this research work:

- The extent of automation for the NCS process lines could be evaluated to know its contribution or the sustenance of NCS industry. Towards this, a basic and preliminary analysis was carried out in the present research works, and is presented in Appendix IV.
- The emerging tools and technologies such as Industry 4.0 principles may be explored to assess their contribution for the sustenance of NCS industry.

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APPENDIX I

Format of the questionnaire to get required data from stakeholders during field studies

Stakeholder group: Date: Time: Place:
Name:

Dear respondent

- Please compare each criterion in the first column with each criterion in row and assign level of relative important using the scale given below.
- Please assign level of relative importance only if the level of importance of column criterion is greater than that of row criterion

	C_1	C_2	C_3	C_4	C_5	C_6	C_7	C_8	C_9	C_{10}	C_{11}
C_1											
C_2											
C_3											
C_4											
C_5											
C_6											
C_7											
C_8											
C_9											
C_{10}											
C_{11}											

	1	3	5	7	9	2,4,6,8
Scale of relative importance	Equal important	Moderate important	Strong important	Very Strong important	Extremely Important	Intermediate values between two adjacent judgements

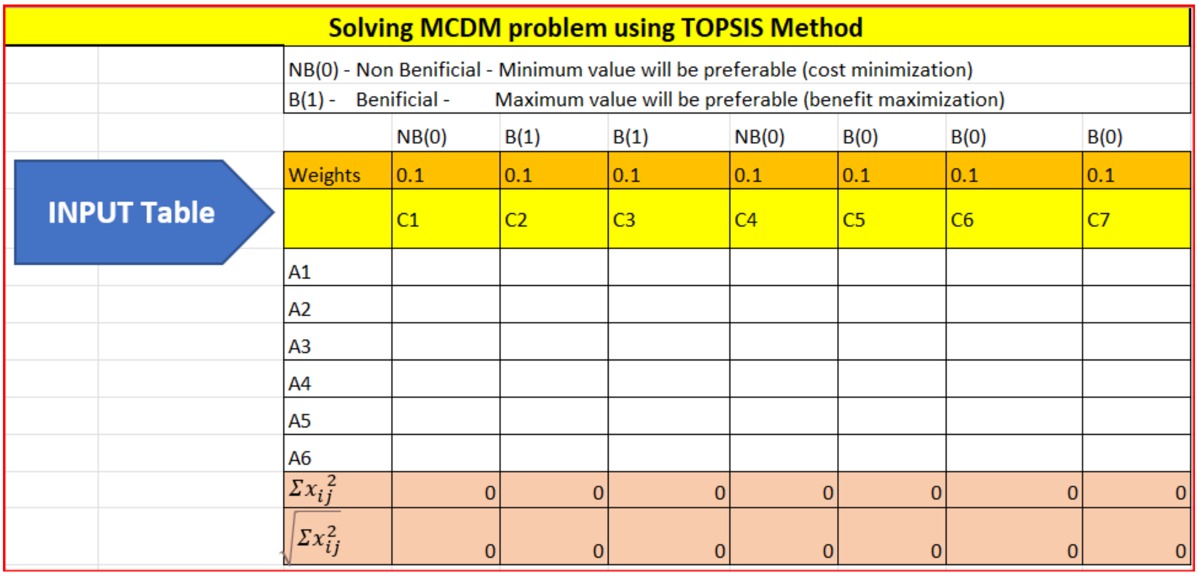
Description of evaluation criteria

C_1
C_2
C_3
C_4
C_5
C_6
C_7
C_8
C_9
C_{10}
C_{11}

APPENDIX II

Following are software inference developed and used for the present research, which can be applied to any kind of decision problem that falls in the similar lines.

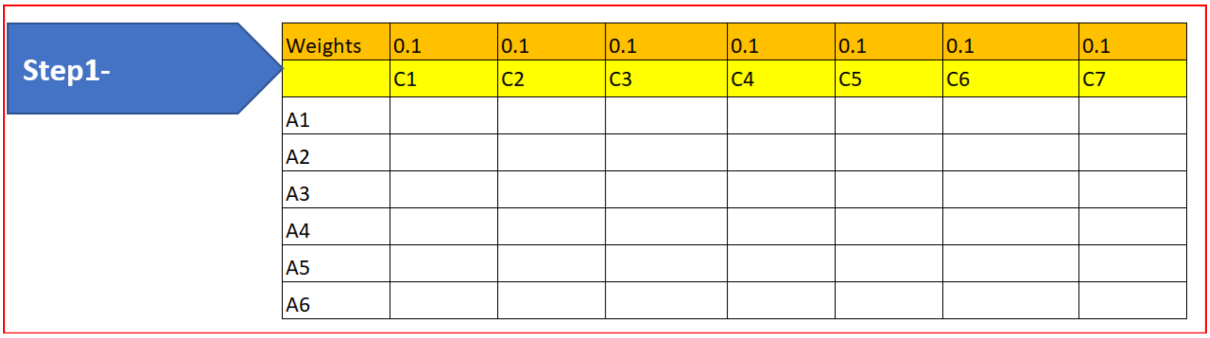
1. TOPSIS interface



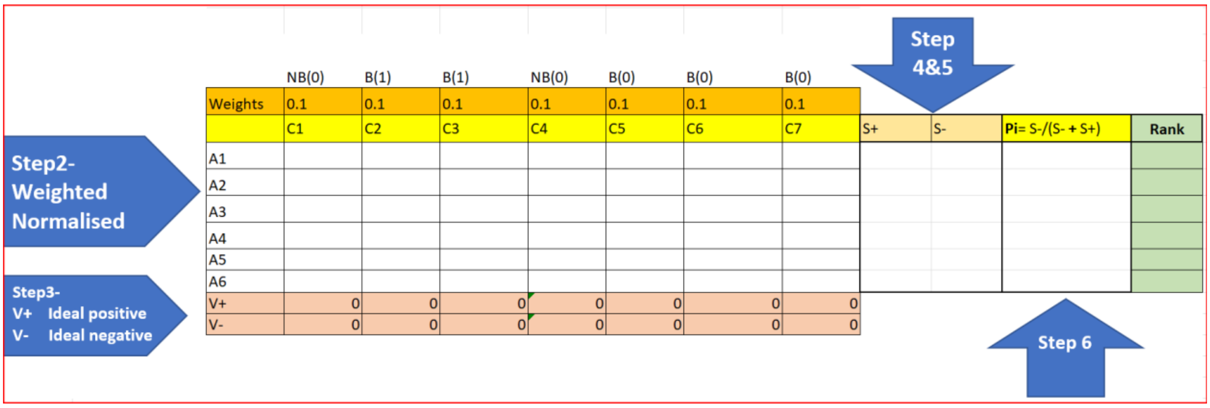
Solving MCDM problem using TOPSIS Method

NB(0) - Non Benificial - Minimum value will be preferable (cost minimization)
B(1) - Benificial - Maximum value will be preferable (benefit maximization)

	NB(0)	B(1)	B(1)	NB(0)	B(0)	B(0)	B(0)
Weights	0.1	0.1	0.1	0.1	0.1	0.1	0.1
	C1	C2	C3	C4	C5	C6	C7
A1							
A2							
A3							
A4							
A5							
A6							
Σx_{ij}^2	0	0	0	0	0	0	0
$\sqrt{\Sigma x_{ij}^2}$	0	0	0	0	0	0	0

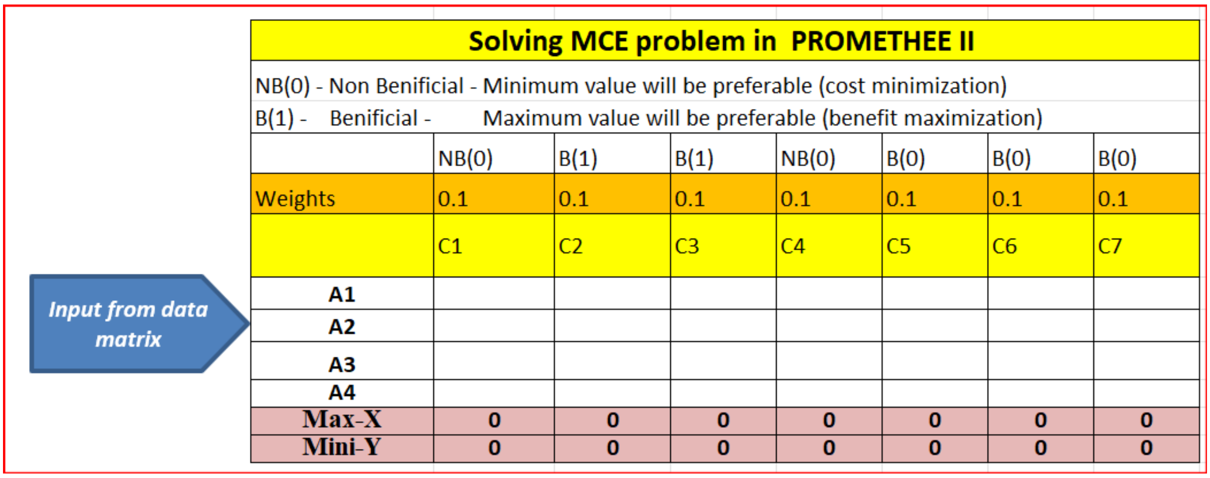


Weights	0.1	0.1	0.1	0.1	0.1	0.1	0.1
	C1	C2	C3	C4	C5	C6	C7
A1							
A2							
A3							
A4							
A5							
A6							



	NB(0)	B(1)	B(1)	NB(0)	B(0)	B(0)	B(0)				
Weights	0.1	0.1	0.1	0.1	0.1	0.1	0.1				
	C1	C2	C3	C4	C5	C6	C7	S+	S-	Pi= S-/(S- + S+)	Rank
A1											
A2											
A3											
A4											
A5											
A6											
V+	0	0	0	0	0	0	0				
V-	0	0	0	0	0	0	0				

2. PROMETHEE II interface

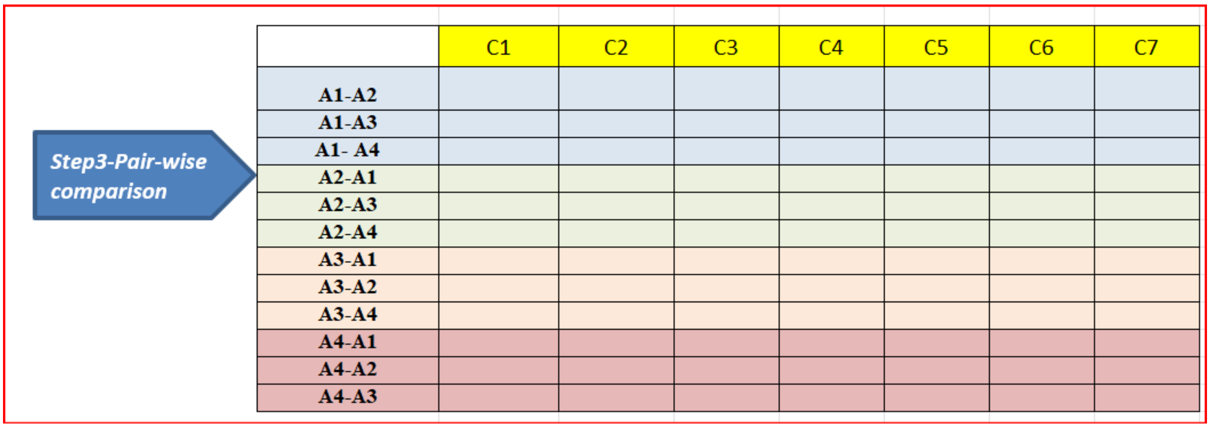


Solving MCE problem in PROMETHEE II

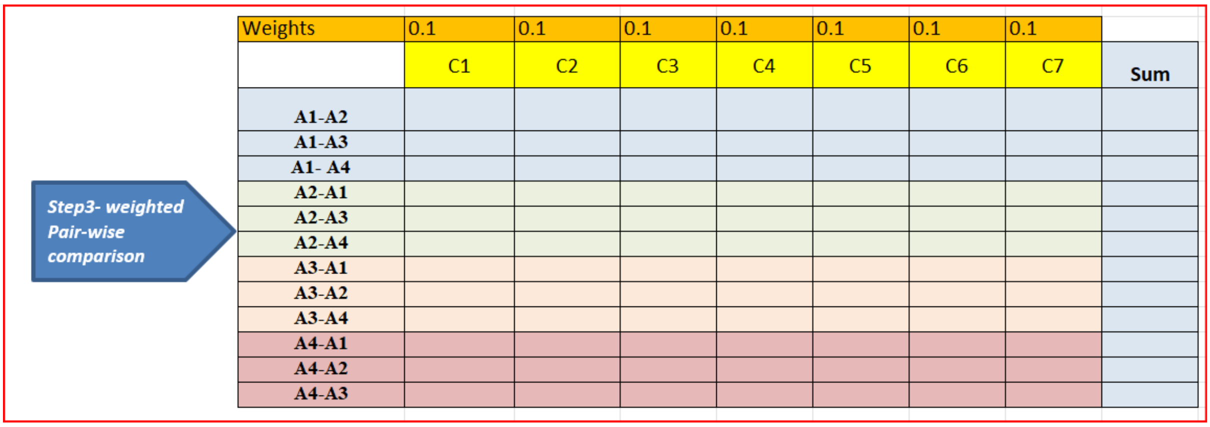
NB(0) - Non Benificial - Minimum value will be preferable (cost minimization)

B(1) - Benificial - Maximum value will be preferable (benefit maximization)

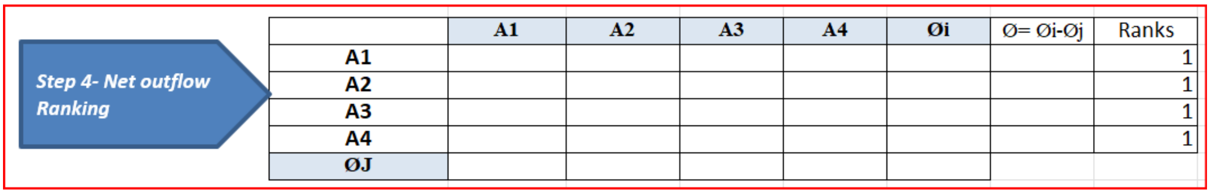
	NB(0)	B(1)	B(1)	NB(0)	B(0)	B(0)	B(0)
Weights	0.1	0.1	0.1	0.1	0.1	0.1	0.1
	C1	C2	C3	C4	C5	C6	C7
A1							
A2							
A3							
A4							
Max-X	0	0	0	0	0	0	0
Mini-Y	0	0	0	0	0	0	0



	C1	C2	C3	C4	C5	C6	C7
A1-A2							
A1-A3							
A1- A4							
A2-A1							
A2-A3							
A2-A4							
A3-A1							
A3-A2							
A3-A4							
A4-A1							
A4-A2							
A4-A3							

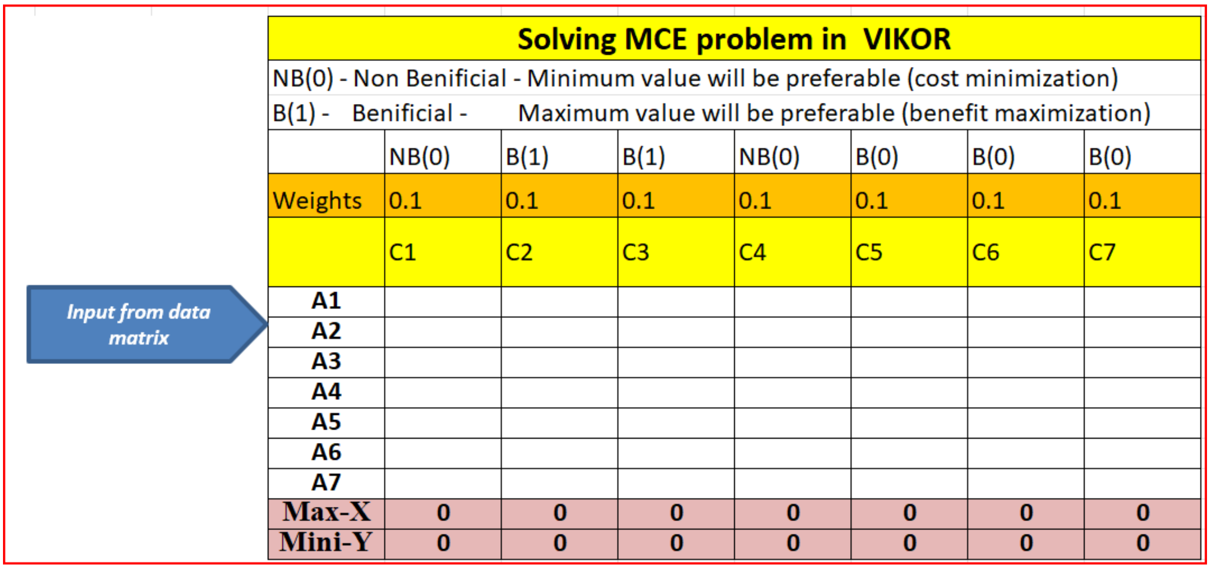


Weights	0.1	0.1	0.1	0.1	0.1	0.1	0.1	
	C1	C2	C3	C4	C5	C6	C7	Sum
A1-A2								
A1-A3								
A1- A4								
A2-A1								
A2-A3								
A2-A4								
A3-A1								
A3-A2								
A3-A4								
A4-A1								
A4-A2								
A4-A3								



	A1	A2	A3	A4	Øi	Ø= Øi-Øj	Ranks
A1							1
A2							1
A3							1
A4							1
ØJ							

3. VIKOR interface

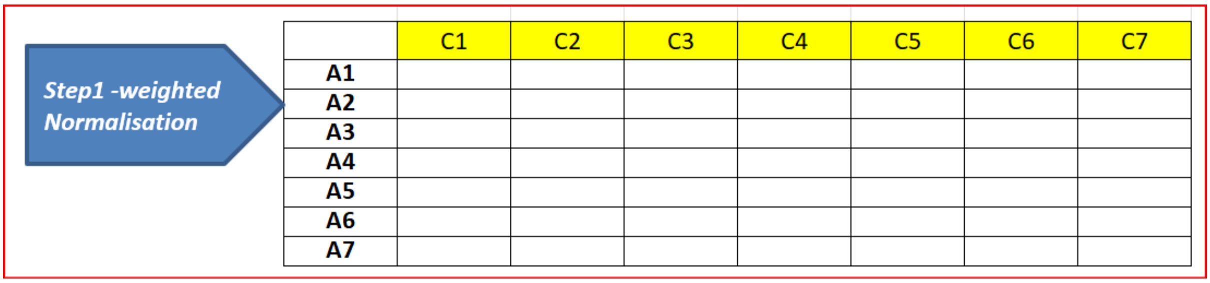


Solving MCE problem in VIKOR

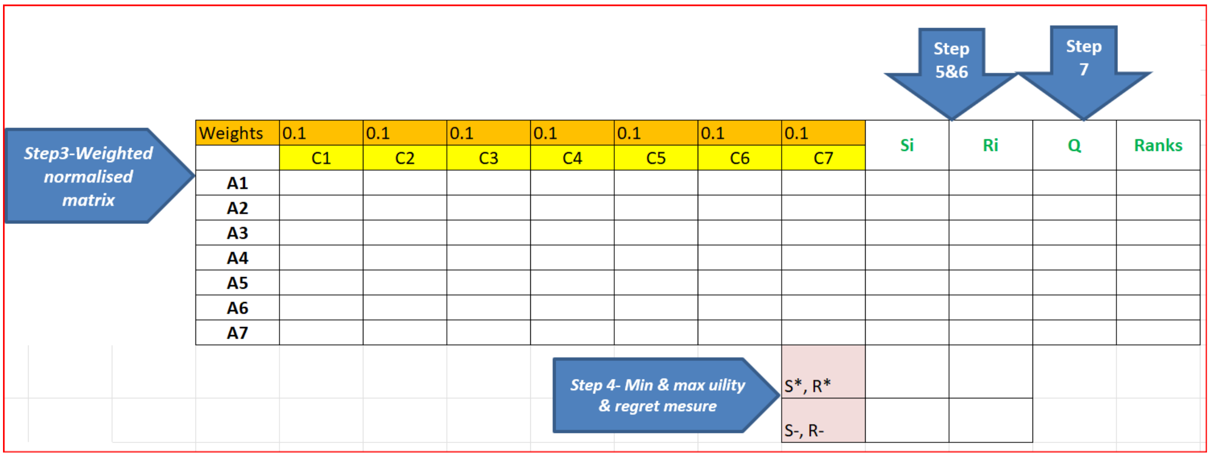
NB(0) - Non Benificial - Minimum value will be preferable (cost minimization)

B(1) - Benificial - Maximum value will be preferable (benefit maximization)

	NB(0)	B(1)	B(1)	NB(0)	B(0)	B(0)	B(0)
Weights	0.1	0.1	0.1	0.1	0.1	0.1	0.1
	C1	C2	C3	C4	C5	C6	C7
A1							
A2							
A3							
A4							
A5							
A6							
A7							
Max-X	**0**	**0**	**0**	**0**	**0**	**0**	**0**
Mini-Y	**0**	**0**	**0**	**0**	**0**	**0**	**0**

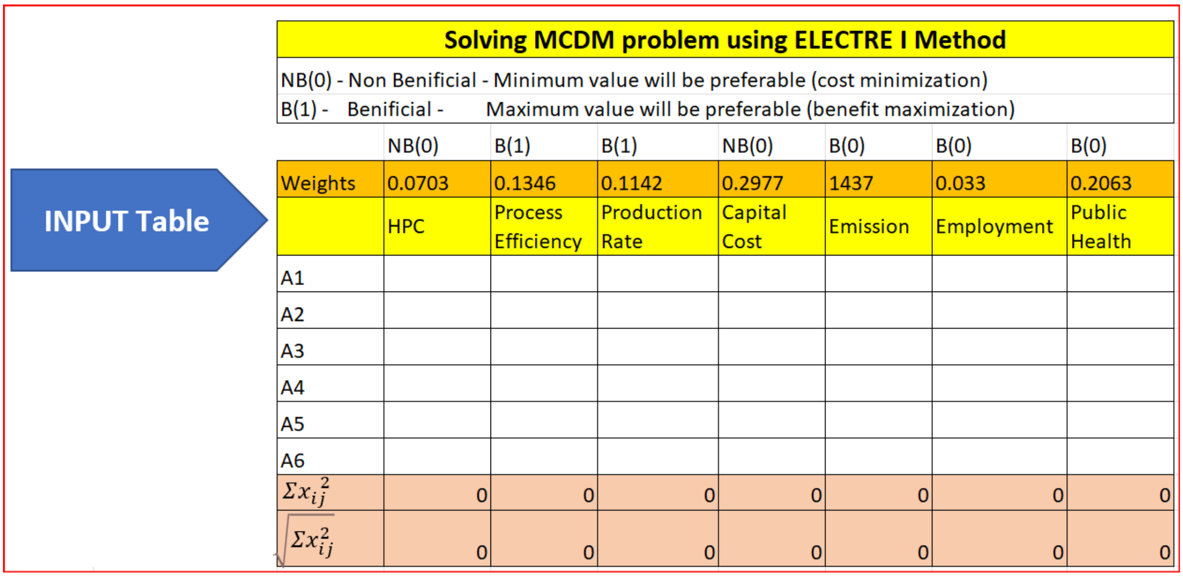


	C1	C2	C3	C4	C5	C6	C7
A1							
A2							
A3							
A4							
A5							
A6							
A7							



Weights	0.1	0.1	0.1	0.1	0.1	0.1	0.1	**Si**	**Ri**	**Q**	**Ranks**
	C1	C2	C3	C4	C5	C6	C7				
A1											
A2											
A3											
A4											
A5											
A6											
A7											
							S*, R*				
							S-, R-				

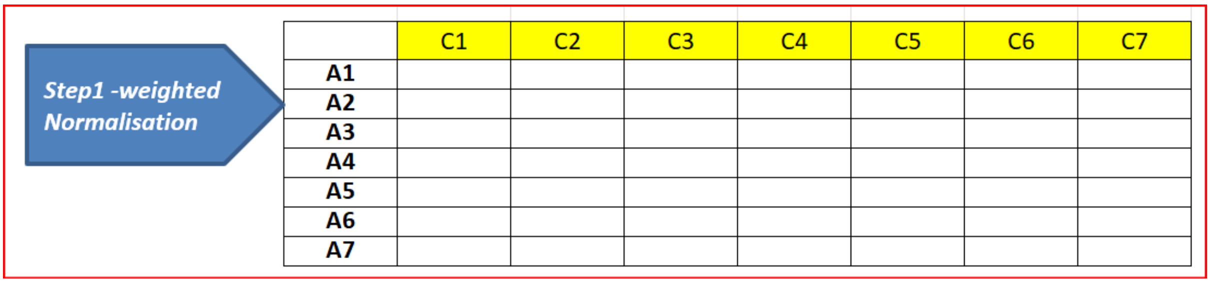
4. ELECTRE I interface



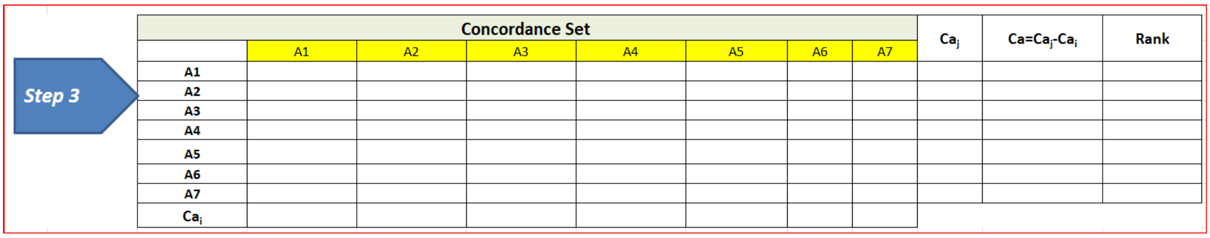
Solving MCDM problem using ELECTRE I Method

NB(0) - Non Benificial - Minimum value will be preferable (cost minimization)
B(1) - Benificial - Maximum value will be preferable (benefit maximization)

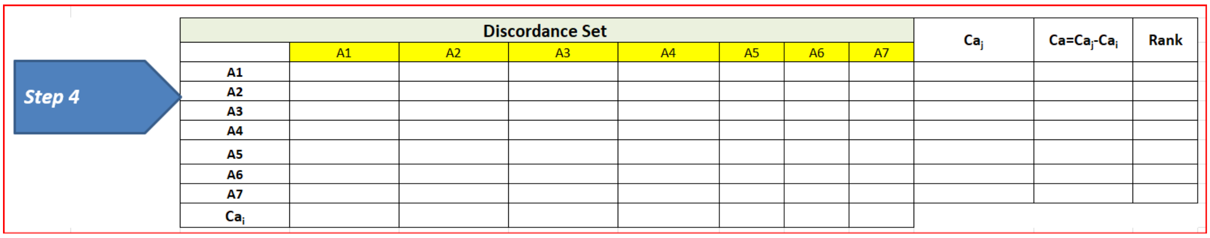
	NB(0)	B(1)	B(1)	NB(0)	B(0)	B(0)	B(0)
Weights	0.0703	0.1346	0.1142	0.2977	1437	0.033	0.2063
	HPC	Process Efficiency	Production Rate	Capital Cost	Emission	Employment	Public Health
A1							
A2							
A3							
A4							
A5							
A6							
Σx_{ij}^2	0	0	0	0	0	0	0
$\sqrt{\Sigma x_{ij}^2}$	0	0	0	0	0	0	0



	C1	C2	C3	C4	C5	C6	C7
A1							
A2							
A3							
A4							
A5							
A6							
A7							



	Concordance Set							Ca_j	$Ca=Ca_j-Ca_i$	Rank
	A1	A2	A3	A4	A5	A6	A7			
A1										
A2										
A3										
A4										
A5										
A6										
A7										
Ca_i										



	Discordance Set							Ca_j	$Ca=Ca_j-Ca_i$	Rank
	A1	A2	A3	A4	A5	A6	A7			
A1										
A2										
A3										
A4										
A5										
A6										
A7										
Ca_i										

APPENDIX III

MCE analysis of appropriate refrigerant-based heat pump dyer for NCS production

MCE to arrive at the most suitable & sustainable refrigerant HPD for drying NCS with respect to NCS production months. The methodology adopted for identifying the appropriate & sustainable refrigerant HPD for drying NCS using MCE as shown below

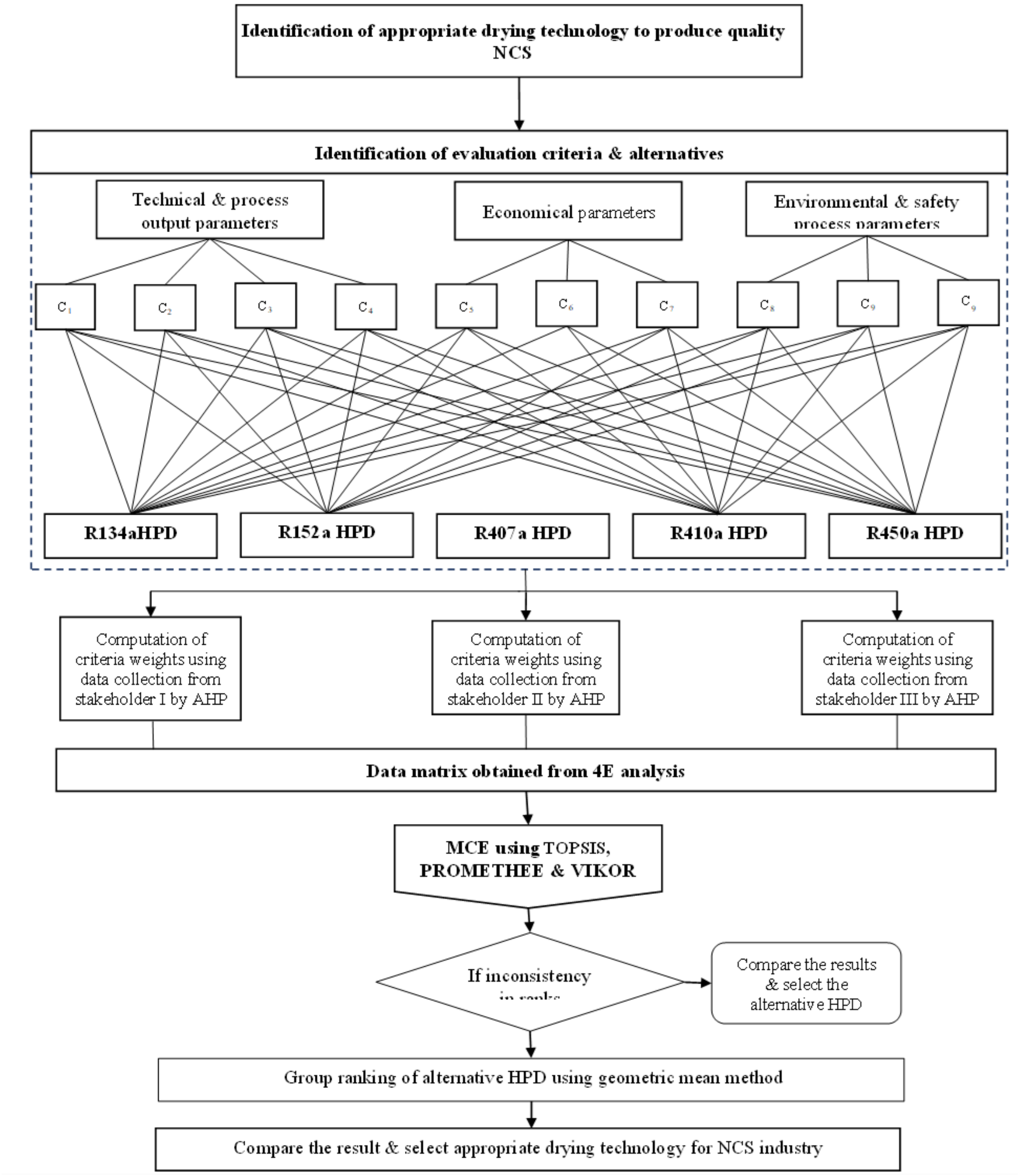


Figure AIII.1. Methodology for selection of appropriate refrigerant HPD for drying NCS

The list of these 10 criteria, along with their nature that is, maximization or minimization, as suitable for selecting the best & sustainable drying technology for NCS production, are as given in Table below.

Table AIII.1. Evaluation criteria, their nature and units

Main criteria		**Sub Criteria**	**Units**	**Maximum/ Minimum**
Technical & Process output parameters	C_1	COP	%	Maximum
	C_2	SEC	kWhr/kg	Minimum
	C_3	SMER	kg/kWhr	Maximum
	C_4	Exergy destruction	kW	Maximum
Economical parameters	C_5	Capital & maintenance cost	₹	Minimum
	C_6	Operational cost	₹	Minimum
	C_7	CO_2 emissions penalty cost	₹	Minimum
Environmental, safety parameters	C_8	$TWEI_{Direct}$	kg of CO_2	Minimum
	C_9	$TWEI_{Indirect}$	kg of CO_2	Minimum
	C_{10}	Flammability	-	Minimum

Table AIII.2. Alternative refrigerants for HPD with its characteristic properties.

Refrigerant	**ODP**	**GWP**	**Toxicity**	**Flammability**
R134a	0	1430	Non-toxic	0
R152a	0	140	Non-toxic	low
R407a	0	2100	Non-toxic	0
R410a	0	1890	Non-toxic	0
R450a	0	604	Non-toxic	0

The following assumptions and the data are considered to estimate, analyze and compare the performance of alternative refrigerant HPD with respect to the ten evaluation criteria covering 4E’s:

i. The atmospheric condition of air at the entry of evaporator are considered same as that of the atmospheric conditions of Anakapalle, Andhra Pradesh, India (the well-established NCS production market for last several decades) for the months September to April (NCS production months).

ii. Temperature & relative humidity of air at dryer inlet are varied from 20-40^{o}C & 30-60%, respectively to achieve the require moisture content NCS. These conditions are good for moisture removal in NCS.

iii. Amount of material to be dried is considered to be 2kgs. Also, initial & final moisture content of NCS is considered to12% and 5%, respectively.

iv. The required drying time to get the required moisture content is considered to be 10 minutes.

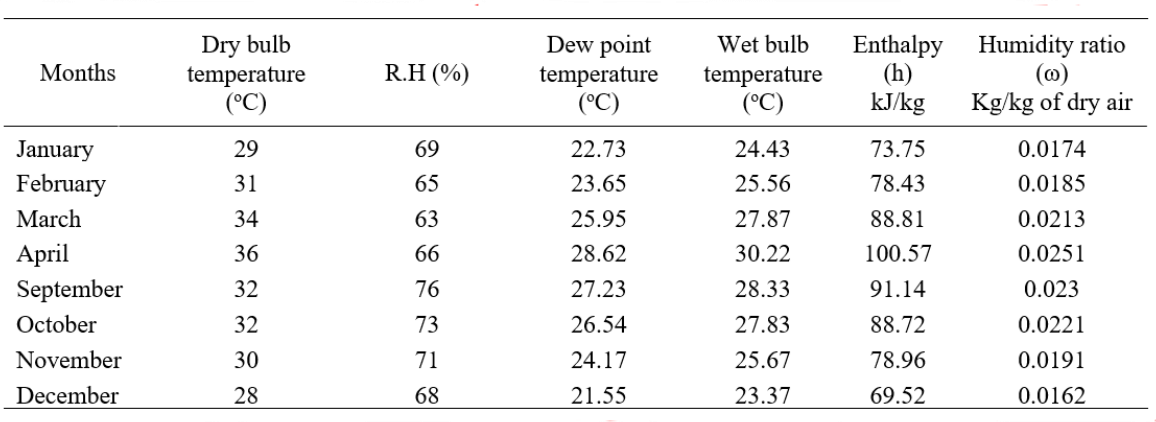
v. Assumption of temperature difference of 5^{o}C between refrigerant and heat exchanger surface.

vi. Bypass factor for evaporator and condenser coil is considered to be 0.2

vii. Mechanical and motor efficiency of compressor is assumed to be 95 and 85%, respectively.

viii. The pressure drop of the refrigerant in different component of heat pump is negligible.

Table AIII.3. Anakapalle atmospheric condition for NCS production months



Months	Dry bulb temperature (°C)	R.H (%)	Dew point temperature (°C)	Wet bulb temperature (°C)	Enthalpy (h) kJ/kg	Humidity ratio (ω) Kg/kg of dry air
January	29	69	22.73	24.43	73.75	0.0174
February	31	65	23.65	25.56	78.43	0.0185
March	34	63	25.95	27.87	88.81	0.0213
April	36	66	28.62	30.22	100.57	0.0251
September	32	76	27.23	28.33	91.14	0.023
October	32	73	26.54	27.83	88.72	0.0221
November	30	71	24.17	25.67	78.96	0.0191
December	28	68	21.55	23.37	69.52	0.0162

The sub-criteria covering all sustainability & 4E of the five eco-friendly based refrigerant HPD were formulated and analyzed by the following established 4E performance model:

(i) Technical & process output parameters

a: COP, SEC, SMER:

The technical & process output parameters viz. COP, SEC, SMER & exergy destruction are computed to analyze the performance of HPD with respect to five considered refrigerant for the atmospheric conditions of Anakapalle, Andhra Pradesh, India for the months September to April (NCS production months). Using the above mention assumptions and specific data, technical & process output parameters the following:

$$m_w = \frac{m_{NCS_{in}}(M_o - M_f)}{100 - M_f}$$

$$M_o = \frac{\left(m_{NCS_{in}} - m_d\right) \text{x}100}{m_i}$$

$$M_f = \frac{\left(m_{NCS_{out}} - m_d\right)\text{x}100}{m_{NCS_{in}}}$$

$$Q_{drying} = m_w * h_{fg}$$

$$m_a = \frac{Q_{drying}}{c_{pam}(T_{ad} - T_{aw}) * d_t}$$

Where, $m_{NCS_{in}}$ is the initial mass of NCS considered to be 2kgs; m_d is the mass of completely dried NCS, h_{fg} is the latent heat of vaporization of water in kJ/kg; c_{pam} specific heat of moist air in kJ/kgK; T_{ad} & T_{aw} are the dry-bulb & wet-bulb temperature of air at dryer inlet in ^{o}C ; d_t is the drying time for required moisture removal in NCS and is considered to be 10 minutes.

Cooling load ($Q_{cooling}$) on the evaporator, heating load ($Q_{heating}$) on the condenser and the compressor work is calculated by the following

$$Q_{cooling} = \dot{m}_a(h_{1a} - h_{2a}) = \dot{m}_r(h_1 - h_4)$$

$$Q_{heating} = \dot{m}_a(h_{3a} - h_{2a}) = \dot{m}_r(h_2 - h_3)$$

$$h_{1a} = c_{pa}T_{1a} + \omega_{1a}\left(h_{fg} + c_{pv}T_{1a}\right)$$

$$h_{2a} = c_{pa}T_{2a} + \omega_{1a}\left(h_{fg} + c_{pv}T_{2a}\right)$$

$$h_{3a} = c_{pa}T_{3a} + \omega_{1a}\left(h_{fg} + c_{pv}T_{3a}\right)$$

$$T_{2a} = T_{aes} + BF(T_{1a} + \ T_{aes})$$

$$T_s = \frac{6687.848}{50.1098 - \ln(ps) - 4.65556\ln\,(T_{aes} + 273.15)} - 273.15$$

$$p_s = \frac{\omega_{aes} * 101.325}{0.62 + \omega_{aes}}$$

$$\omega_{aes} = \frac{\omega_{3a} - BF * \omega_{1a}}{1 - BF}$$

$$T_{re} = T_{aes} - 5$$

$$T_{acs} = \frac{T_{3a} - BF * T_{2a}}{1 - BF}$$

$$T_{rc} = T_{acs} + 5$$

$$W_{compressor} = \dot{m}_r(h_2 - h_1)$$

$$h_2 = \frac{h_{2s} - h_1}{\eta_{isen}} + h_1$$

$$\eta_{isen} = \frac{\eta_v}{exp^{\left[-2.28\frac{T_{re}+273}{T_{rc}+273}+2.67\right]}}$$

$$\eta_{isen} = 1.04\left(1 + 0.1\frac{T_{evaporator} + 273}{100}\right)exp^{\left(-0.066\frac{p_{condenser}}{p_{evaporator}}\right)}$$

$$COP = \frac{Q_{heating}}{W_{compressor}}$$

$$SMER = \frac{m_w}{W_{in}}$$

$$SEC = \frac{W_{in}}{m_w}$$

Where, $h_{1a}, h_{2a}, h_{3a}, h_{4a}$ are enthalpies of air at their respective state points in kJ/kg; h_1, h_2, h_3, h_4 are the enthalpies of refrigerant at their respective state points in kJ/kg; $T_{1a}, T_{2a}, T_{3a}, T_{4a}$ are the temperature of air at their respective state points in ^{o}C, BF is the bypass factor ; c_{pa} & c_{pv} is the specific heat of dry air and water vapor respectively, kJ/kgK; T_{aes} is the evaporator surface temperature in ^{o}C and is assumed to be less than the dew point temperature of air at the inlet of the heat pump by successive iteration method using the following equation ; p_s is the saturated vapor pressure (kPa); ω_{aes} is the specific humidity of air at evaporator surface (kg/kg of dry air); T_{re} & T_{rc} are the temperature of refrigerants in evaporator & condenser , respectively in ^{o}C; T_{acs} is the condenser surface temperature in ^{o}C; $W_{compressor}$ is the compressor work in kW; η_{isen}& η_v are the isentropic & volumetric efficiency of compressor; COP is the coefficient of performance of HPD; $SMER$ is the specific moisture extraction rate in kg/kWhr; SEC is the specific energy consumption in kWhr/kg.

b: Exergy destruction:

The another technical & process output that is total exergy destruction of HPD in both refrigerant and air side is computed by neglecting the kinetic and potential energy of the refrigerant and also the changes in the chemical composition. Exergy performance of HPD for drying the NCS is computing by the following models:

$$Ex_{HPD} = Ex_{compressor} + Ex_{condenser} + Ex_{evaporator} + Ex_{expansion} + Ex_{dryer}$$

$$Ex_{compressor} = W_{in} + \dot{m}_r\{(h_1 - h_o) - T_o(s_1 - s_o)\} - \dot{m}_r\{(h_2 - h_o) - T_o(s_2 - s_o)\}$$

$$Ex_{condenser} = \dot{m}_r\{(h_1 - h_o) - T_o(s_1 - s_o)\} - \dot{m}_r\{(h_3 - h_o) - T_o(s_3 - s_o)\} + \dot{m}_a c_{pam}\left[(T_{2a} - T_o) - T_o\left(\frac{T_{2a}}{T_o}\right)\right] - \dot{m}_a c_{pam}\left[(T_{3a} - T_o) - T_o\left(\frac{T_{3a}}{T_o}\right)\right]$$

$$Ex_{evaporator} = \dot{m}_r\{(h_4 - h_o) - T_o(s_4 - s_o)\} - \dot{m}_r\{(h_1 - h_o) - T_o(s_1 - s_o)\} + \dot{m}_a c_{pam}\left[(T_{1a} - T_o) - T_o\left(\frac{T_{1a}}{T_o}\right)\right] - \dot{m}_a c_{pam}\left[(T_{2a} - T_o) - T_o\left(\frac{T_{2a}}{T_o}\right)\right]$$

$$Ex_{exapansion} = \dot{m}_r\{(h_3 - h_o) - T_o(s_3 - s_o)\} - \dot{m}_r\{(h_4 - h_o) - T_o(s_4 - s_o)\}$$

$$Ex_{dryer} = \dot{m}_a c_{pam}\left[(T_{3a} - T_o) - T_o\left(\frac{T_{3a}}{T_o}\right)\right] - \dot{m}_a c_{pam}\left[(T_{4a} - T_o) - T_o\left(\frac{T_{4a}}{T_o}\right)\right]$$

Where, T_o, h_o & s_o are the temperature (°C), enthalpy (kJ/kg) & entropy (kJ/kgK) values of dead state of the refrigerant respectively.

(ii) Economic parameters

The economic performance of the HPD for achieve the require moisture content NCS is analysed by the following:

$$Cost_{capital\,\&maintenance} = (Cost_{evaporator} + Cost_{compressor} + Cost_{condenser} + Cost_{expansion} + Cost_{pump})\psi * CRF$$

$$Cost_{evaporator} = 30000 * \left(\frac{Area\ of\ evaporator}{10}\right)^{0.85}$$

$$Cost_{condenser} = 30000 * \left(\frac{Area\ of\ condenser}{10}\right)^{0.85}$$

$$Cost_{compressor} = \frac{39.5 * \dot{m}_r}{0.9 - \eta_{global}} \cdot \frac{p_{condenser}}{p_{evaporator}} . \ln\left(\frac{p_{condenser}}{p_{evaporator}}\right)$$

$$Cost_{pump} = 2100 * \left(\frac{1 - \eta_{pump}}{\eta_{pump}}\right)^{0.5} * \left(\left(Q_{heating}\right)^{0.26} + \left(Q_{cooling}\right)^{0.26}\right)$$

$$CRF = \frac{IR(1 + IR)^n}{(1 + IR)^n - 1}$$

$$Cost_{operational} = W_{compressor} * 365 * d_t * Cost_{eletricity}$$

$Cost_{electricity}$ is the unit cost of electricity in India

$$Cost_{CO_2 penaly} = \beta * 365 * d_t * \left(\frac{Q_{cooling}}{COP}\right) * unit\ cost_{CO_2}$$

β is the carbon dioxide emission faction for unit cost of electricity

Where, ψ is the maintenance factor and is considered; IR is the rate of interest and is considered to be 14%; n is the lifetime of the equipment and is considered to 10 years; β is the carbon dioxide emission fraction for unit cost of electricity with reference value in India; $Cost_{eletricity}$ is the unit electricity cost in India; $unit\ cost_{CO_2}$ is the unit damage cost due to carbon dioxide emission with reference value in India.

(iii) Environmental parameters

Environmental impact of HPD was assessed by computing the TEWI (Total Equivalent Warming Impact). Similar methodology is extensively used in previous literature works to assess the environmental impact operated when used with various refrigerants TEWI for the considered refrigerant HPD for drying NCS to achieve the require moisture is carried out by the following:

$$TEWI_{Direct} = GWP * m_{ref} * L_{rate} * L_{time} + GWP * m_{ref} * \left(1 - \alpha_{recup}\right)$$

$$TEWI_{Indirect} = 365 * d_t * [Q_{cooling}/COP] * \beta * L_{time}$$

Where, α_{recup} is the refrigerant life recovery rate which is considered to be 70% (if refrigerant mass less than 100kg), L_{time} is the economical useful life considered to be as 15 years and L_{rate} is the annual rate of refrigerant replacement & leaks and is considered be 12.5% and GWP is the global warming potential of vary with respect to refrigerant.

Table below presents the consolidated data matrix of 5 ecofriendly refrigerant based HPD for 10 evaluation criteria covering technical & process output, economic, environmental & safety parameters elicited through 4E analysis.

Table AIII.4. Data matrix

Alternative HPD	Evaluation criteria									
	C_1	C_2	C_3	C_4	C_5	C_6	C_7	C_8	C_9	C_{10}
R134a	6.2753	1.741	0.575	1.286	2671.71	275.51	35.66	121.57	954.21	0.5
R152a	6.3809	1.712	0.584	1.266	2663.52	271.82	35.06	7.39	938.32	0.75
R407a	6.0683	1.801	0.555	1.331	2681.21	287.45	36.87	180.17	986.62	0.5
R410a	6.0745	1.798	0.556	1.329	2679.11	286.91	36.83	142.47	985.56	0.5
R450a	6.2528	1.747	0.572	1.291	2673.11	294.67	35.78	55.02	957.52	0.5

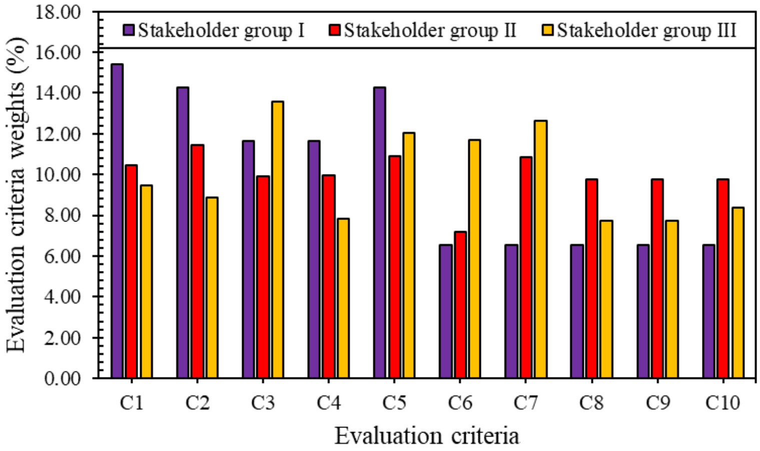


Figure AIII.2. AHP weights of criteria with respect to individual stakeholders

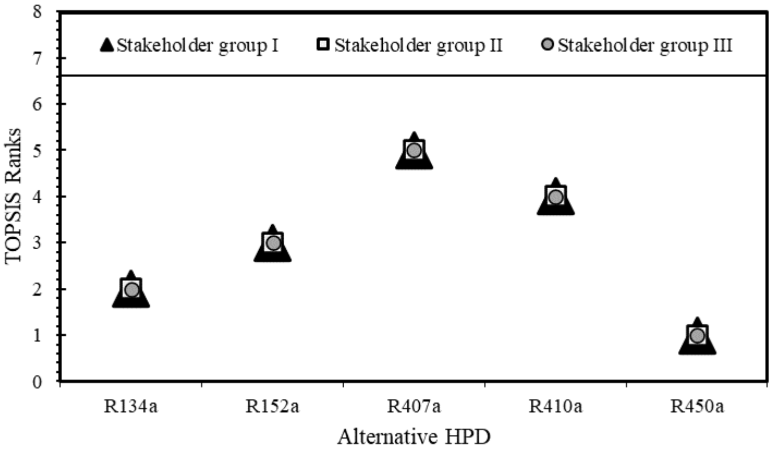


Figure AIII.3. Ranking of alternative HPD in TOPSIS

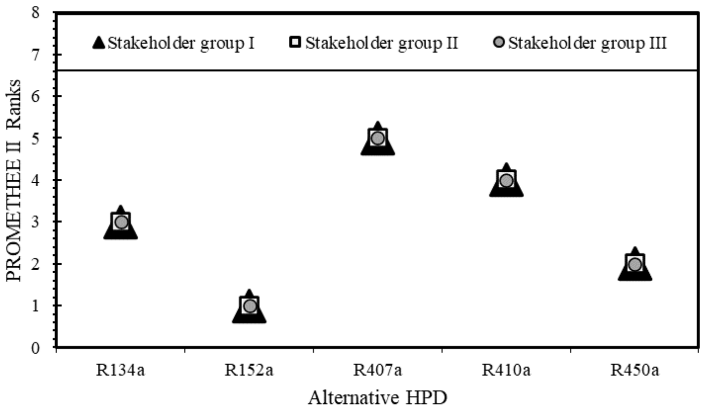


Figure AIII.4. Ranking of alternative HPD in PROMETHEE II

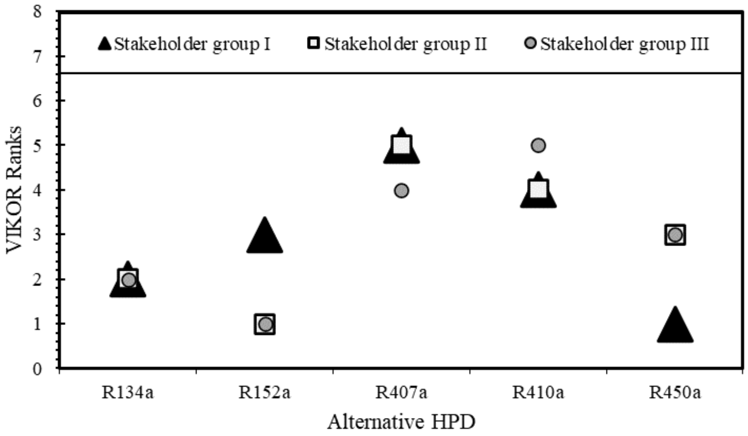


Figure AIII.5. Ranking of alternative HPD in VIKOR

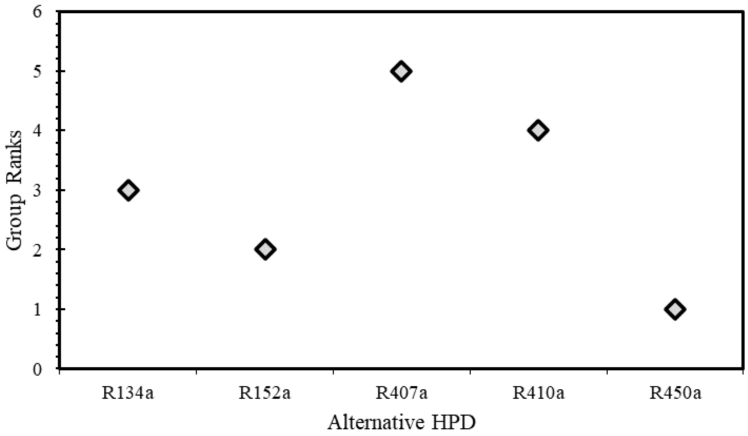


Figure AIII.6. Group ranking of alternative HPD for NCS industry.

APPENDIX IV

The quantitative measure of LoA should not only take into consideration the type of task but also the effect of particular task. The complexity, criticality, and difficulty of each task vary from one another. Therefore, assessment of LoA of process line should take into consideration of specific task and its effect. Figure below demonstrate the methodology for assessing LoA for each process line for NCS industry.

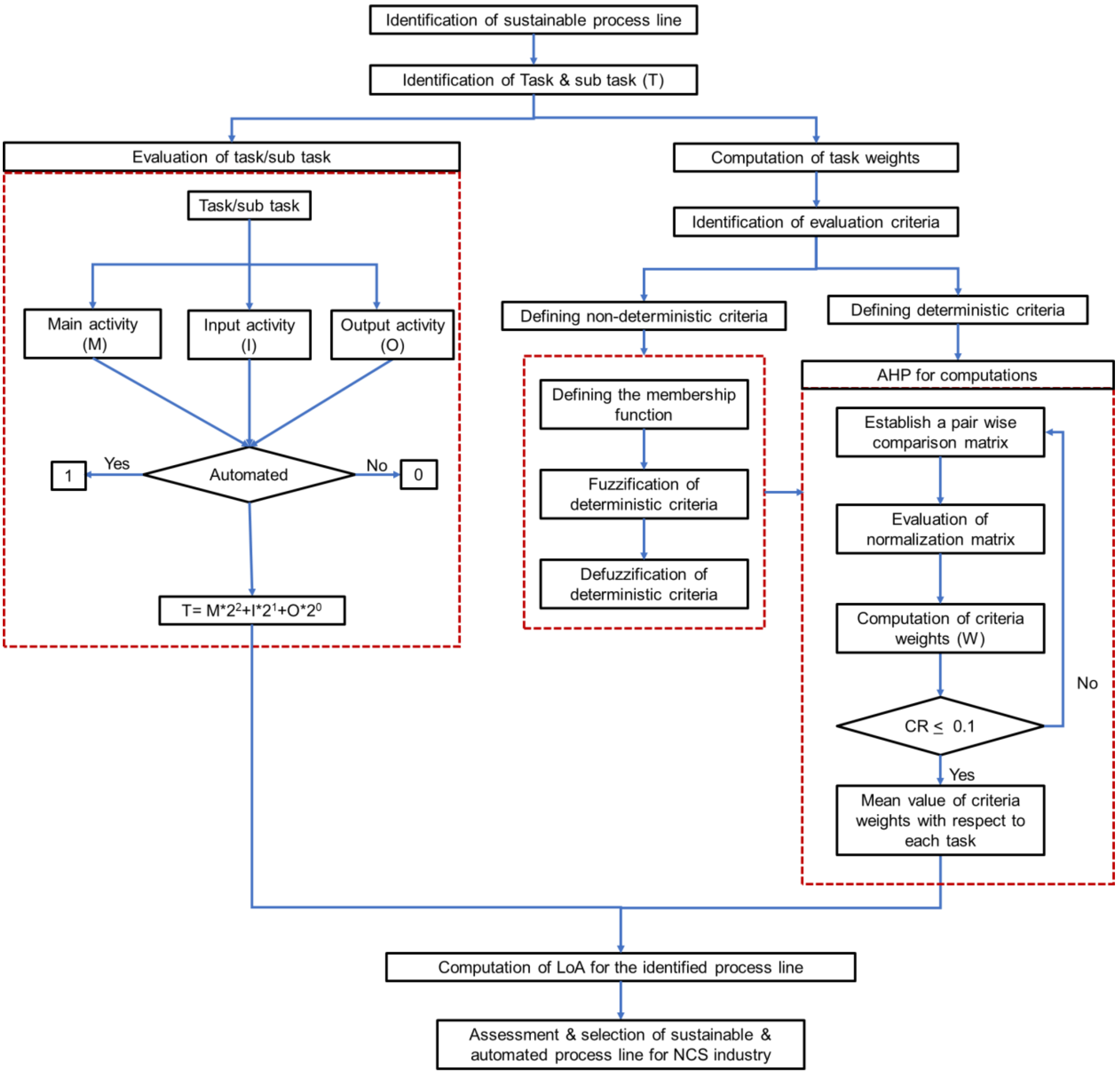


Figure AIV.1. Methodology for assessing LoA process line for NCS industry

Table presents the sustainable methods at each process unit from the published works. For each process unit two sustainable methods were considered and arrived at sixteen possible alternative sustainable process lines for NCS production

Table AIV.1: Sustainable methods at each process unit of NCS process line

Operation	Identified Sustainable Method	Notation	Reference
Juice Extraction	Horizontal single horizontal crusher that run on electricity without hot water	SHEN	[10,11]
	Multi-horizontal roller without hot water	MHEN	
Juice Clarification	Clarification with Plant mucilage	C1	[12]
	Chemical Clarification	C2	
Juice Evaporation	Modified single pan evaporation unit	E1	[13]
	Single Pan evaporation	E2	
Drying	Open Sun Drying	D1	
	Forced convection drying	D2	[14]

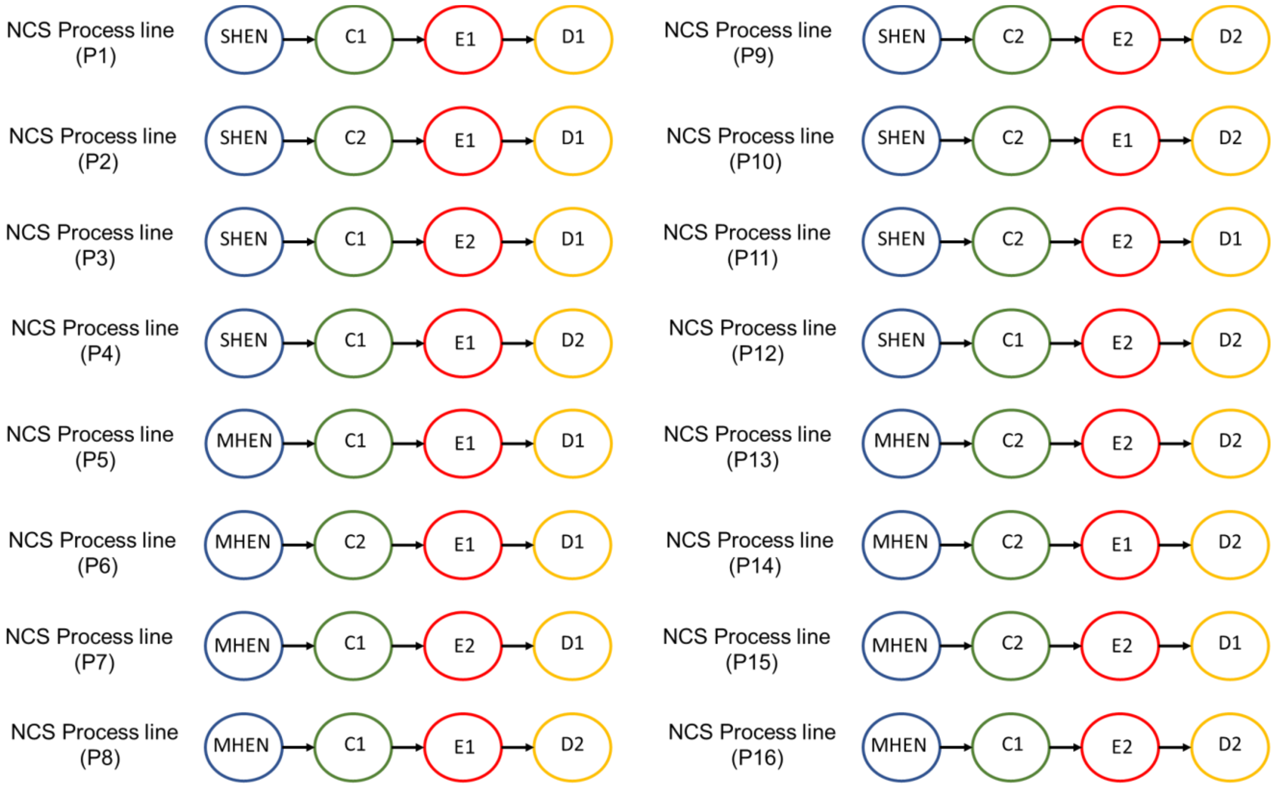


Figure AIV.2. Alternative sustainable process lines for NCS production

Table AIV.2. Task involved in each sub-process of NCS production

Task		Sub-task	Operation involved
Juice extraction	T1	Cane preparation	1. Washing 2. Cane chopping
	T2	Crushing	1. Cane feeding 2. Addition of water 3. Cane crushing 4. Juice collection 5. Bagasse collection
Juice clarification	T3	Screening	1. Setting the juice 2. Removing the impurities
	T4	Addition of lime	1. Juice collection in boiling pan 2. Lime addition
	T5	Addition of clarifires	1. Preparation of clarificants 2. Addition of Clarifires 3. Stirring 4. Removal of scum
Juice Evaporation	T6	Preparation of furnace	1. open sun drying of bagasse 2. Addition & combustion of bagasse
	T7	Heating of Juice	1. Juice heating 2. Stirring
	T8	Juice concentration	1. Addition of cooking oil 2. Stirring 3. Test for required concentration
Drying	T9	Drying	1. Moisture removal 2. Moulding

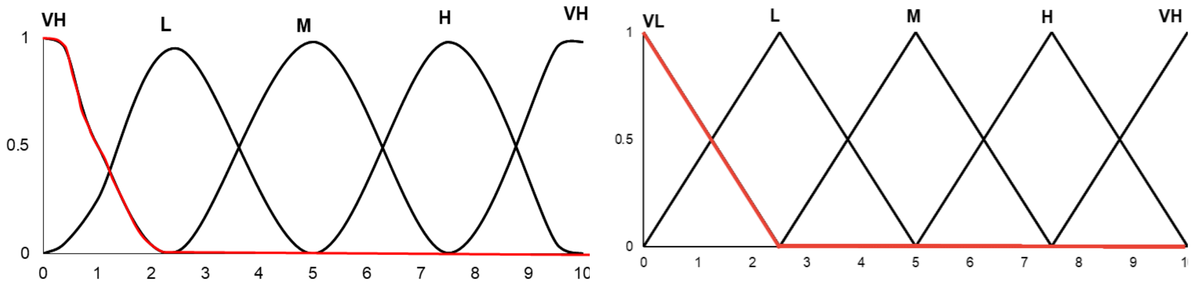
Table AIV.3. Evaluation criteria for assessing LoA of NCS production process

S.No.	Criteria	Definition	Units	Min/Max
C1	Complexity	The extent of difficulty to carry out each task involved in NCS production process.	-	Min
C2	Quality	The measure of characteristic output for each task of NCS production process	-	Max
C3	Man hours	Time taken by each person to complete each task of NCS production process	Hours	Min
C4	Production rate	The measure of output of each task with respect to each task of NCS production	kg/hr	Min
C5	Economic Factors	The total cost involved to carry out each task of NCS production	INR	Min

Table AIV.4. Conditions to define work preference

Quality	Complexity	Work preference
VH	VL	VH
VH	L	H
M	L	M
M	VL	M
L	L	L
L	VL	L
VL	VL	VL

VL: very low, VH: very high, L: low, H: high, M: medium,



(i) (ii)

Figure AIV.3. Membership function to define (i) quality (ii) complexity

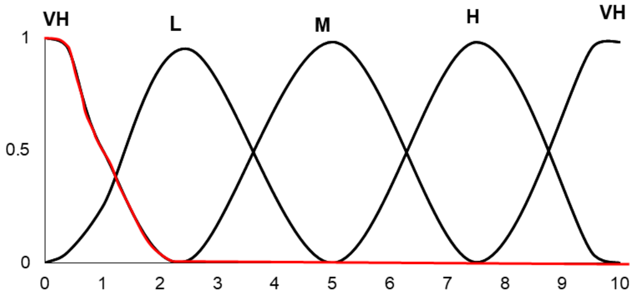


Figure AIV.4. Membership function to define work preference

$$\mathrm{LoA}_{\mathrm{Process-line}} = \left(\sum_{\mathbf{i=1}}^{\mathbf{n}} \mathbf{T_i W_i} \middle/ \sum_{\mathbf{i=1}}^{\mathbf{n}} \mathbf{T_{max} W_i}\right) * \mathbf{100}$$

$$\mathrm{LoA}_{\mathrm{Process-line}} = \left(\sum\nolimits_{\mathbf{i=1}}^{\mathbf{n}} \mathbf{T_i W_i / 7}\right) * \mathbf{100}$$

Where:

- Ti = Task level automation
- Wi= Average criteria weightage of each task of a particular NCS process line (obtained by AHP)
- T_{max}= maximum value for task level automation equal to 7
- n = The total number of sub-tasks involved in the given process line

Table AIV.5. Task level automation assessment values

Main task		Sub task	Possible sustainable NCS process lines															
			P1	P2	P3	P4	P5	P6	P7	P8	P9	P10	P11	P12	P13	P14	P15	P16
Juice extraction	T1	Cane preparation	0	0	0	0	2	2	2	2	0	0	0	0	2	2	2	2
	T2	Crushing	2	2	2	2	2.4	2.4	2.4	2.4	2	2	2	2	2.4	2.4	2.4	2.4
Juice clarification	T3	Screening	2	2	2	2	2	2	2	2	2	2	2	2	2	2	2	2
	T4	Addition of lime	4	4	4	4	4	4	4	4	4	4	4	4	4	4	4	4
	T5	Addition of clarifiers	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
Juice evaporation	T6	Preparation of furnace	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
	T7	Heating of juice	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
	T8	Juice concentration	1.33	1.33	1.33	1.33	1.33	1.33	1.33	1.33	1.33	1.33	1.33	1.33	1.33	1.33	1.33	1.33
Drying	T9	Drying	2	2	2	2.67	2	2	2	2.67	2.67	2.67	2	2.67	2.67	2.67	2	2.67

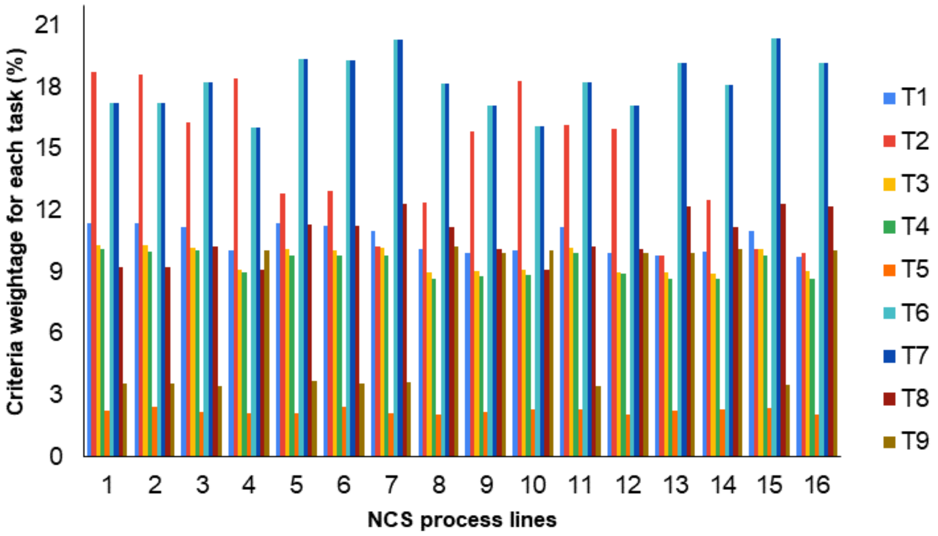


Figure AIV.4. Membership function to define work preference

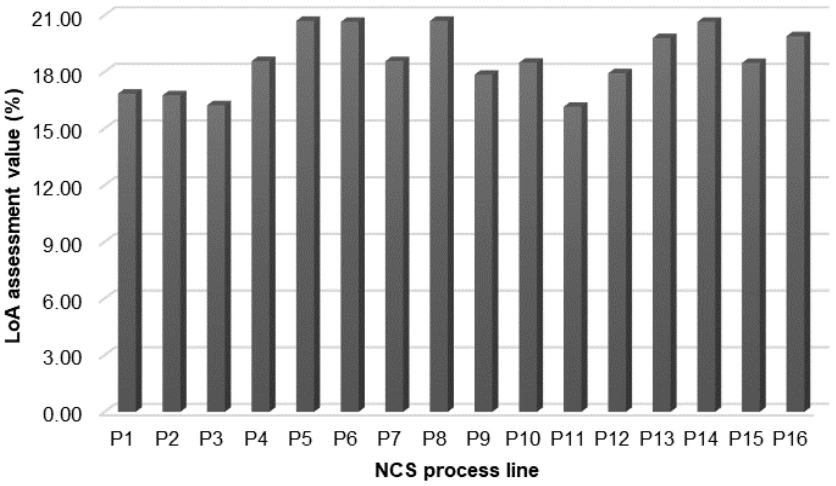


Figure AIV.5. LOA assessment value of identified sixteen process lines

List of Publications and Presentations

a. International Journals (SCI/SCIE)

1. **Beeram Sravya**, Srinivas M, Raj, S. P., & K.S. Reddy. (2020). Selection of sustainable juice extraction techniques for non-centrifugal sugar industry using multi-criteria decision-making methods. *Journal of Food Process Engineering*, 43(7). https://doi.org/10.1111/jfpe.13415.
2. Srinivas, M., **Sravya, B.**, Raj, S. P., & Reddy, K. S. (2020). Crushing method selection for non-centrifugal sugar production by FAHP–ELECTRE I. *International Journal of Low-Carbon Technologies*, *15*(3), 328-335. https://doi.org/10.1093/ijlct/ctz081
3. **Beeram Sravya** & Srinivas M. (2021). Sustainable juice evaporation unit selection for non-centrifugal sugar industry using multi-criteria evaluation methods. *Journal of Food Process Engineering*. https://doi.org/10.1111/jfpe.13906
4. **Beeram Sravya**, Srinivas, M., & Raj, S. P. (2022). An Experimental-MCE Based Analysis to Identify Appropriate Process Conditions for Producing Quality Non-centrifugal Sugar. *Sugar Tech*, 1-14. https://doi.org/10.1007/s12355-022-01201-8
5. **Beeram Sravya** & Srinivas M. Selection of sustainable drying technology for non-centrifugal sugar industry using multi-criteria decision-making methods. *Journal of Stored Products Research.* **(Under review)**
6. **Beeram Sravya** & Srinivas M. Selection of Suitable Heat Pump Dryer for NCS Production using Multi-criteria Evaluation Techniques. *International Journal of Refrigeration.* **(Under review)**
7. **Beeram Sravya** & Srinivas M. Assessment of level of automation for non-centrifugal sugar industry. *Journal of food process engineering.* **(Under review)**

b. International Conferences

1. **Beeram, S**., Morapakala, S., Deshmukh, S. S., & Sunkara, P. R. (2020). Selection of suitable and sustainable clarificants and clarification method for non-centrifugal sugar production using MCE. Materials Today: Proceedings, 28, 893-897.*https://doi.org/10.1016/j.matpr.2019.12.319.*

2. **Beeram Sravya** & Srinivas M. (2021). Selection of suitable heat transfer fluid for modified evaporation unit of NCS production. Journal of Physics: Conference Series.

Biography

1. Biography of the Candidate

Ms. B. Sravya is a Research Scholar in the Department of Mechanical Engineering at Birla Institute of Technology & Science (BITS) Pilani, Hyderabad Campus. She has completed her Masters in Tool Design from Osmania University in 2015. She obtained her Bachelor's degree in Mechanical Engineering from Vardhaman College of Engineering in 2013. Prior to her Ph.D., she has a teaching experience for over 3 years where she taught several Mechanical Engineering subjects. Her research interests include sustainability assessment, multi-criteria evaluation techniques and applications.

2. Biography of the Supervisor

Prof. Morapakala Srinivas has been associated with BITS-Pilani for the last 24 years in various teaching, administrative and research capacities. During his tenure he served BITS-Pilani, Pilani, Hyderabad and Dubai campuses. He is a graduate from REC, Warangal and a post graduate from JNTU-Hyderabad and Ph.D. from BITS-Pilani.

His research interest includes renewable energy commercialization and energy efficiency in process industries, thermal engineering and multi-criteria decision making. He has published his research works widely in well reputed peer-reviewed international journals and conferences. In connection with his research activities, he visited well reputed universities such as University of Nottingham, University Exeter, Herriot-Watt University, all in UK and Honkong Polytechnic University, Honkong; Hubei University, China. He is the recipient of ₹ 48 Lakh worth project, funded by Royal Academy of Engineering, UK to revive the sugarcane based jaggery industry in India and UK. This project viz. STEEJ, was completed recently in collaboration with IIT Madras and Herriot watt university, UK. He has been a reviewer for several well reputed international journals in the area of renewable energy.

He has been a resource person for various training programs in the areas of renewable energy and thermal engineering for officials of central government of India as well as Government of Egypt. He has been the author of data book for heat transfer applications. He has been associated with organizing good number of international conferences and workshops in the area of renewable energy and energy efficiency in process industries.

3. Biography of the Co-supervisor

Prof. Sandip Shridharrao Deshmukh is presently a Professor at the Department of Mechanical Engineering, Birla Institute of Technology and Science, Pilani (BITS Pilani), Hyderabad Campus. He obtained his B.E in Mechanical Engineering from Amaravati University ; M.E. in Thermal Power Engineering from Amaravati University; Ph.D. from BITS Pilani in the year 2006 and Post-Doctoral research fellow from University of Surrey, Guildford, UK between 2008-2012. He has published around 52 papers in reputed international journals, presented more than 35 research works in National and International Conferences, holds Patents on Solar Distillation Apparatus and filed 3 other patents. He was awarded with Prof. SSR Memorial Teaching Excellence Award - 2021 instituted by BITS Alumni. Prof. Sandip S. Deshmukh is presently giuding 04 Ph.D. and guided/guiding several graduate and undergraduate students. His teaching and research interests include IC engines, renewable energy planning and system sizing, refrigeration and air conditioning and thermodynamics and heat transfer.