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# Development of a decision support framework considering sustainability for the selection of thermal food processes

DISSERTATION

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## STATUTORY DECLARATION

I declare that I have authored this thesis independently, that I have not used other than the declared sources / resources, and that I have explicitly marked all material which has been quoted either literally or by content from the used sources.

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# Abstract

In this study, an integrative framework has been developed that provides decision support in selecting suitable thermal process technologies considering sustainability of the process. The selection procedure comprises two main steps: the preliminary selection step which narrows the range of technologies appropriate for the given product, and the final selection step which provides the ratings and rankings of the pre-selected technologies according to a set of criteria. This framework can be applied to support decisions in either selecting new facilities or changing the used technologies of the existing facilities.

Based on the combination of rule-based technique, analytic hierarchy process and fuzzy logic, the proposed framework is supposed to be applicable for various thermal processes in food industry including blanching, pasteurization, sterilization, boiling, cooking, drying, etc. In order to ensure to cover the wide range of technologies available on the market and to facilitate the evaluation of process sustainability, the thermal process systems are subdivided into three separate subsystems following the sequence of energy flow in the process.

Rule-based technique is firstly employed in the preliminary selection of technologies for a product under consideration. The selection principally bases on the technical specifications of the subsystem technologies and the given products. In the final selection step, fuzzy analytic hierarchy process is used for the rating and ranking of the pre-selected technology alternatives. The parameters for the appraisal of sustainability are aggregated into three major indicators: environmental, economic and social performances. Energy performance is particularly considered in this step due to the fact that thermal processes are the most energy-intensive unit operation in food manufacturing sector. Dealing with the insufficiency and uncertainty facing in most decision making problems, the data for the rating and ranking procedure is generally specified in triangular fuzzy number.

The proposed framework has been successfully tested in the development of a decision support system for food dryer selection. The core components of this decision support system are the database of drying technologies and food products and the database of dryer's performance with respect to the energy, economic and social criteria. A huge amount of data

has been carefully screened in order to make the databases as exhaustive and consistent as possible. The decision support system has been successfully implemented in two case studies for selecting coconut dryers and of cassava starch dryers.

These new integrative approach and decision support system for food dryer selection are expected to provide relevant contributions to the field of rational selection of manufacturing technologies and equipment that is still unsatisfying and insufficient.

**Keywords:** decision support system, rule-based technique, analytic hierarchy process, fuzzy set, thermal process technology, food industry

# Kurzfassung

In dieser Studie wurde ein integratives System entwickelt, das eine Entscheidungshilfe bei der Auswahl geeigneter thermischer Verfahren in der Lebensmittelverarbeitung, unter Berücksichtigung der Nachhaltigkeit der Prozesse, darstellt.

Das Auswahlverfahren besteht aus zwei wesentlichen Schritten: der erste Schritt dient der Vor-Auswahl, der die für ein Produkt möglichen Technologien eingrenzt. In einem zweiten Schritt werden die vorab ausgewählten Technologien nach einer Reihe von Kriterien bewertet und endgültig ausgewählt.

Dieses Entscheidungssystem kann angewendet werden, um bei der Auswahl von neuen Anlagen oder bei Änderungen der eingesetzten Technologien in bereits bestehenden Einrichtungen, zu unterstützen.

Basierend auf der Kombination von regelbasierten Verfahren, Analytic Hierarchy Process und Fuzzy-Logik, ist das vorgeschlagene Decision Support System für verschiedene thermische Prozesse in der Lebensmittelindustrie (einschließlich Blanchieren, Pasteurisieren, Sterilisieren, Kochen, Trocknen, etc.) anwendbar. Um zu gewährleisten, dass die breite Palette von am Markt verfügbaren Technologien abgedeckt ist und um die Auswertung von Prozessnachhaltigkeit zu erleichtern, werden die thermischen Prozesssysteme in drei Subsysteme, angelehnt an den Energiefluss, unterteilt.

Das regelbasierte Verfahren wird zunächst in der Vorauswahl von Technologien für ein Produkt eingesetzt, wobei sich die Auswahl hauptsächlich auf technische Spezifikationen der Technologien des Subsystems und auf die jeweiligen Produkte stützt. In der Endauswahl werden auf Fuzzy-Logic basierte Analytic Hierarchy Processes für das Rating und Ranking der vorab ausgewählten Technologiealternativen verwendet. Die Beurteilung der Nachhaltigkeit wird nach drei wichtigen Indikatoren vorgenommen: ökologische, ökonomische und soziale Kriterien. Da thermische Prozesse die energieintensivsten im Nahrungsmittelsektor sind, wird die Energieintensität der Prozesse bei der Bewertung der Nachhaltigkeit mitbetrachtet. Um mit der Unsicherheit und dem Mangel an Daten im Entscheidungsfindungprozess umgehen zu

können, werden die Daten für das Rating und Ranking-Verfahren im Allgemeinen in triangularen Fuzzy-Zahlen angegeben.

Das Auswahlverfahren wurde erfolgreich zur Erstellung eines Decision Support Systems für die Auswahl von Lebensmittel-Trocknern verwendet. Die Kernkomponenten dieses Decision Support Systems sind die Datenbank der Trocknungstechnologien, der Lebensmittel, und der Leistungsfähigkeit der Trockner in Bezug auf energetische, wirtschaftliche und soziale Kriterien. Dabei wurde eine große Menge an Daten sorgfältig ausgewählt, um die Datenbanken möglicht zu vervollständigen. Das Decision Support Systems wurde anhand von zwei Fallstudien erfolgreich getestet: bei der Trocknerauswahl von Kokosnüssen und von Maniokstärke.

Dieser neue integrative Ansatz und das Decision Support System für die Auswahl von Lebensmitteltrocknern ist ein wichtiger wissenschaftlicher Beitrag auf dem Gebeit der rationalen Auswahl von Fertigungstechnologien und Anlagen, welches bisher noch nicht ausreichend erforscht wurde.

**Schlüsselwörter:** Decision Support System, regelbasierte Techniken, Analytic Hierarchy Process , Fuzzy-Set, thermische Verfahrenstechnik, Lebensmittel

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# Acronyms

| | |
|---|---|
| AHP | Analytic hierarchy process |
| Btu | British thermal unit |
| CAT | Computer aided technology |
| CHP | Combined heat and power |
| COP | Coefficient of performance |
| DEF | Dryer efficiency factor |
| DSS | Decision support system |
| ES | Expert system |
| FBD | Fluidized bed dryer |
| GAIA | Geometrical analysis for interactive aid |
| GHG | Greenhouse gas |
| HPD | Heap pump dryer |
| IEA | International Energy Agency |
| lb | International avoirdupois pound |
| MCDM | Multiple criteria decision making |
| PROMETHEE | Preference Ranking Organization METHod for Enrichment Evaluation |
| RH | Relative humidity |
| SMER | Specific moisture evaporation rate |

| | |
|---|---|
| STEC | Specific thermal energy consumption |
| TAA | Total antioxidant activity |
| TFN | Triangular fuzzy number |
| TOPSIS | Technique for Order Preference by Similarity to Ideal Solution |
| UNIDO | United Nations Industrial Development Organization |

# Symbols

### *Abbreviations*

| *Symbol* | *Definition* | *Unit* |
|---|---|---|
| *c* | Specific heat capacity | kJ/kg.°C |
| *h* | Enthalpy of drying air | KJ/kg |
| *m* | Mass | kg/batch or kg/s |
| *P* | Vapor pressure | Bar |
| *Q* | Thermal energy | kJ/batch or kJ/s |
| *r* | Ratio of exhaust air recovery | % |
| *R* | Ratio | % |
| *T* | Temperature | °C |
| *w* | Moisture content on wet basis | kg/kg |
| *x* | Moisture content on dry basis | kg/kg |
| *y* | Humidity ratio | kg/kg dry air |
| *Y* | Relative humidity | % |
| *μ* | Enthalpy efficiency of heat exchanger | - |
| *ΔH* | Latent heat | kJ/kg |

### *Subscripts*

| *Substance* | | *State* | | *Process* | |
|---|---|---|---|---|---|
| *a* | Drying air | *atm* | Ambient | *C* | Condensation |
| *d* | Dry basis | *dp* | Dew point | *D* | Conductive drying |
| *m* | Material | *f* | Frozen | *E* | Evaporation |
| *w* | Water | *i* | Inlet | *F* | Freezing |
| | | *o* | Outlet | *FD* | Freeze drying |
| | | *v* | Vapor | *He* | Heating |
| | | | | *L* | Loss |
| | | | | *M* | Melting |
| | | | | *S* | Sublimation |
| | | | | *Rec* | Recovery |
| | | | | *Renew* | Renewable energy |
| | | | | *V* | Vaporization |

### *Fuzzy number arithmetic*

| | |
|---|---|
| $\oplus$ | Addition |
| $\ominus$ | Subtraction |
| $\otimes$ | Multiplication |
| $\oslash$ | Division |

# 1. INTRODUCTION

## 1.1 THERMAL FOOD PROCESSES - AN OVERVIEW

Thermal processes, involving heating and cooling, remain the most important methods in processing of foods, vegetables and fruits.

The most obvious characteristic of industrial thermal processes is high energy consumption. Processes like drying, evaporation, pasteurization, boiling, freezing, and cooling may consume a substantial amount of 70% of the total industrial energy use (Steinbuks, 2010). These processes, on the other hands, have very high energy saving potential. Many energy-efficient thermal process systems have been developed and commercialized, that significantly reduce primary energy use, increase energy savings and present prominent economic benefit.

### 1.1.1 Thermal food processes

Thermal food processes involve raising the product to some final temperature that depends on the particular objective of the process (Delgado et al., 2005). Most food processing operations require thermal energy at temperature in the range of -50°C to 250°C that covers two areas of food engineering: application of heat or heating (including blanching, cooking, drying, pasteurization, sterilization) and removal of heat or cooling (including chilling, freezing, and cold storage). The main objectives of thermal processing of food products are:

- Minimize possible health hazards from pathogenic micro-organisms;
- Alter the eating quality of foods;
- Extend the shelf life of foods.

The following table presents the important heating processes in food industry and their applications.

Table 1-1. Common heating processes in food industry

| ***Thermal process*** | ***Purpose*** | ***Processing feedstock*** | ***Temperature range***[1] | ***Heating medium*** |
|---|---|---|---|---|
| Blanching | Destroy enzyme activity prior to further processing<br>Brighten the color of some foods<br>Soften the texture of vegetables | Fruit juices, fruits and green vegetables, mushrooms | 80 - 100°C | Steam or hot water. hot oil |
| Pasteurization | Inactivate the pathogenic micro-organism activity<br>Extend the shelf life of foods | Liquid food, liquid egg | 62 - 90°C | Steam or hot water, hot oil |
| Sterilization | Destroy microbial and enzyme activity<br>Extend the shelf life of foods to several months for storage at ambient temperature | Many types | 110 - 130°C | Steam, hot water or flames |
| Evaporation or concentration | Remove water from liquid foods<br>Reduce transport cost<br>Pre-concentrate foods prior to drying, freezing or sterilization | Liquid food | 50 - 100°C | Steam or hot gas |
| Distillation | Separate the volatile compounds | Alcoholic spirits, volatile flavor and aroma compounds | | Steam, hot water |
| Drying and Dehydration | Remove water from food in order to extend the shelf life of food products | Many types of foods | -50 - 250°C | Hot air, steam, hot water |

[1]Data taken from the Reference Document on Best Available Techniques in the Food, Drink and Milk Industries (IPPC, 2006)

| *Thermal process* | *Purpose* | *Processing feedstock* | *Temperature range*[1] | *Heating medium* |
|---|---|---|---|---|
| Baking and roasting | Alter the taste and texture of foods<br>Stabilize the texture of e.g. foams<br>Destroy the micro-organisms and reduce water activity at the surface of the food | Flour-based foods, fruits and vegetable;<br>Meats, coffee, nuts, cacao, chicory, fruit, cereals | 110 - 240°C | Hot air or infrared irradiation |
| Cooking and boiling | Alter the texture, color and moisture content of foods | Ready-to-eat meal or meal components (meat) | | Steam, hot water. hot oil |
| Frying | Alter the texture, color and moisture content of foods<br>Destroy the micro-organisms and reduce water activity at the surface of the food | Raw materials (fish, potatoes, chicken) | 190 - 205°C | Hot oil |

Source: Fellows (2000)

Heating processes play a very important role in the food industry. They take part in the production of nearly all products and numerous unit operations in the processing of foods, vegetables and fruits.

### 1.1.2 Energy consumption

Among the main energy users of the industrial sector, food manufacturing is responsible for nearly 10% of the total energy consumption (IEA, 2010). In the food sector, thermal processes make up the largest proportion (over 75%) of the sector's energy use, while other operations like motor driven systems (pumps and fans, mixers, conveyors and other equipment) and facilitate functions (space heating, ventilation, lighting, etc) comprise approximately 20% of the energy requirement (ICF, 2007; Baldwin, 2009).

In Figure 1-1, the benchmarking data of specific heat consumption in the processing of a number of food and vegetable products indicates the significant difference compared to electricity consumption. Several products like fish, vegetable oil, whey and milk powder, energy for heating and cooling processes are responsible for up to 90% of the total energy consumption.

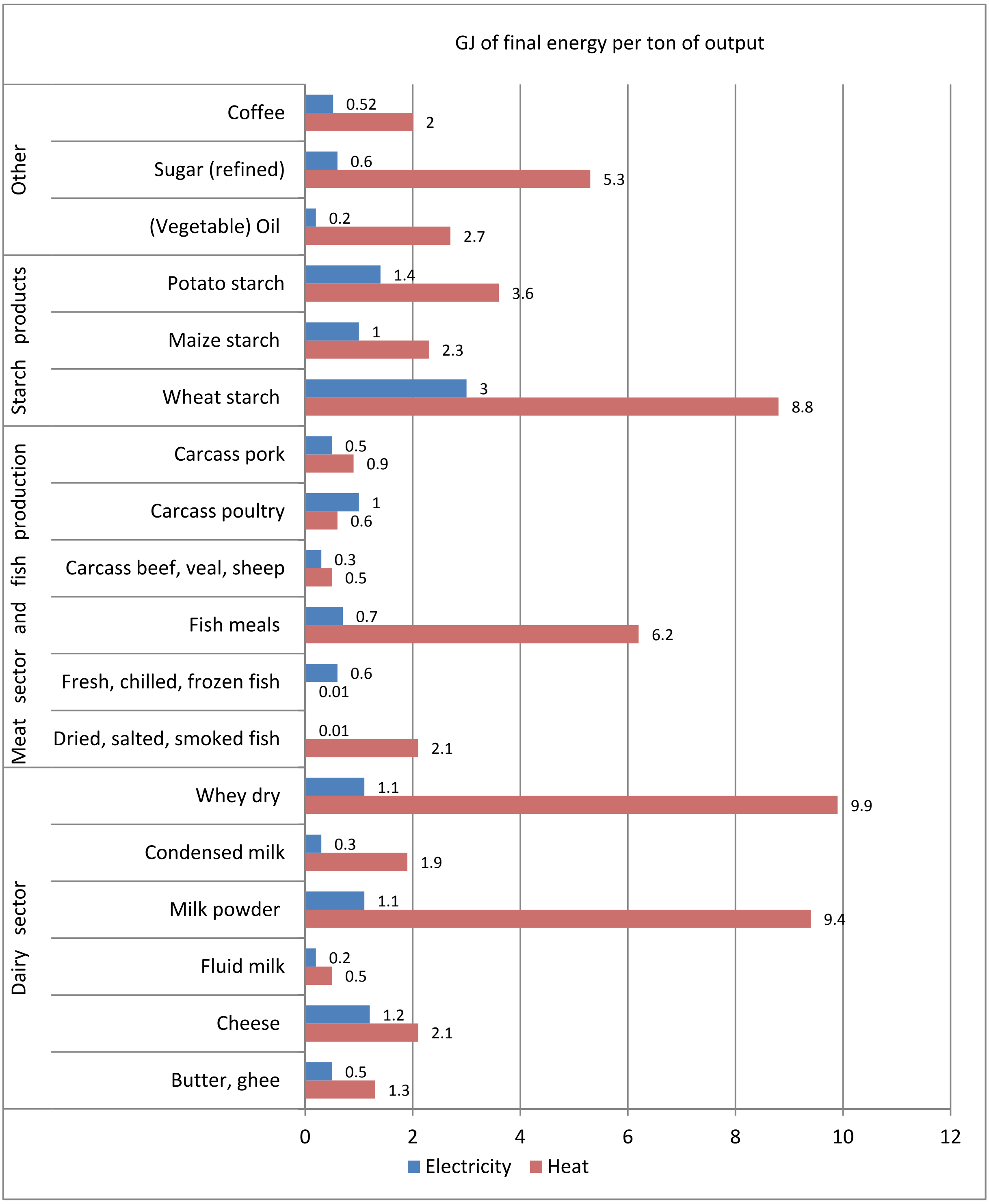


Figure 1-1. Specific energy consumption of selected products of the food and beverage sector in OECD countries (data taken from UNIDO, 2010)

Besides, in the processing of many food products, concentration, dehydration, pasteurization, and cooking are among the most energy-intensive unit operations. As can be seen in the breakdowns of energy consumption of several key thermal process operations in the dairy sector in Figure 1-2, concentration is the largest energy-intensive operation in the production of powder milk and canned evaporated milk, while making vat and cooking are respectively the highest ones in the productions of cheese and yogurt.

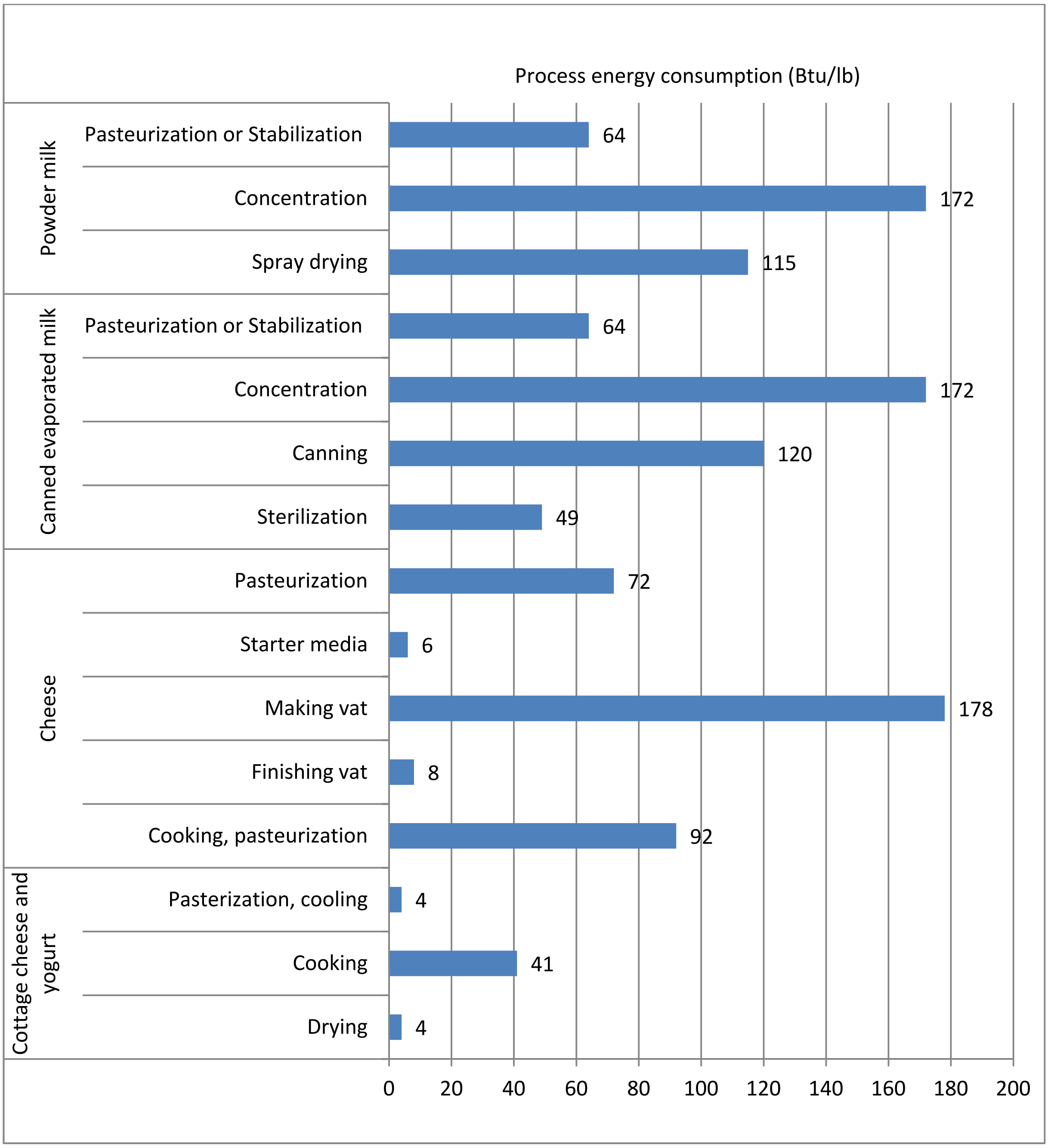


Figure 1-2. Energy consumption of some key thermal processes in dairy industry (data taken from Brush et al., 2011)

### 1.1.3 Energy saving opportunity

These processes, on the other hands, have very high energy saving potential. The key opportunities for improved energy efficiency in food manufacturing sector include:

- Efficient energy management
- Process optimization
- Technology upgrade and innovation
- Waste heat recovery and combined heat and power (CHP)

The International Energy Agency (IEA) estimated the energy saving potentials of the food and beverages sector as being 0.7 EJ[2]/year in the industrialized countries and 1.4 EJ/year in developing countries, equivalent to the improvement potentials of 25% in industrialized countries and 40% in developing countries respectively (UNIDO, 2010). The energy improvement potentials identified in this report suggest that production costs could be reduced up to 10%.

It is noteworthy that redesigning and upgrading thermal process equipment can yield the largest energy efficiency improvements. While this may require significant resources and investment, it often yields great savings. If the existing thermal food equipment is old, inefficient and significantly oversized, the most effective solution is to replace it with modern high-efficiency equipment. Technology changes not only cut the fuel bills but also reduce the pollution output of the process. Evaluation of viability of equipment retrofit and replacement opportunity for food industry in United States of America represents a medium magnitude considering the financial, technical, institutional and regulatory barriers facing the sector (IEA, 2010). In the context of old-fashioned and backward facilities happens in many developing countries, this opportunity can represent greater viability.

[2]Exajoule, 1 EJ = $10^{18}$ J

## 1.2 RATIONAL SELECTION OF THERMAL FOOD PROCESSES

For the reasons mentioned above, energy efficiency is supposed one of the most important criteria whenever considering investment decision for the thermal food processes. However, the importance of energy savings has been widely underestimated in practice. Obviously, in the conventional financial justification models like net present value, benefit cost ratio, internal rate of return, or payback period, energy expenditure is usually taken into account as a type of operation costs, but they fail to capture the non-financial impacts of inefficient energy consumption, for instance the problems of greenhouse gas emission, non-renewable resource depletion, energy recovery encouragement, etc.

The development of multiple criteria decision making (MCDM) techniques enables engineers to account for both financial and non-financial attributes in the decision making process. Various MCDM models have been developed to provide decision support in manufacturing process selection. Although, most decision support systems for manufacturing equipment selection reported in the literature remain ineligible to interpret the authentic contribution of energy issue into the rational final solution.

Among the key thermal food processes, the selection of drying technologies is one of the most complex processes due to the fact that there is a great diversity of drying technologies and each of these technology types has a wide assortment of sub-categories. A reliable dryer selection decision should rely on many aspects such as the process specifications, final product quality, economic efficiency, and safety and environmental considerations (Crapiste & Rotstein, 1997), such as the availability of energy in a suitable form (Heß, 1984). However it has been found that the development of decision support system for dryer selection is still insufficient and unsatisfying.

## 1.3 RESEARCH STATEMENTS

The overall objective of this study is to develop an integrative framework in order to provide decision support for the selection of appropriate technologies considering sustainability of the thermal processes. The study will concentrate on the processes involving the application of heat such as boiling, drying, blanching, etc. Processes involving removal of heat (freezing, cooling) will not be considered in the study.

The appraisal of sustainability of the thermal food processes covers three main aspects: environmental, social and economic performances. Dealing with the fact that energy usage is always of greatest concern of most thermal food processes, energy performances with respect to energy efficiency, energy recovery and renewable energy consumption are particularly considered in the selection of the technologies.

Dealing with multiple criteria decision making problems, this framework provides decision support at the early stage of selecting appropriate technologies for thermal food processes for either the selection of new facilities or the technology change of the existing facilities. The obtained results can be the input for the more in-depth selection procedures such as bench-scale test or pilot-scale trial.

As a validation of this integrative approach, a computational model was developed for the selection of food drying technologies. Applying the proposed methodology to develop a computer-based DSS for drying process can benefit from the following advantages:

- This will be a typical but comprehensive computer-based DSS for the selection of thermal processes due to the fact that drying is the process of greatest complexity and diversified technologies.
- This will provide a relevant contribution to the field of computer-based DSS for the selection of drying technologies that is still unsatisfying and insufficient.

Case studies are carried out to examine the applicability and reliability of the proposed DSS. Choosing the food processing companies in Vietnam as the base-case alternatives for the application of changing the used technologies, it is expected to promote the mordernisation of the food drying processes which still challenge the old-fashioned and backward situation and to foster the trend of drying technology transition toward sustainability.

# 2. DECISION SUPPORT SYSTEM IN INDUSTRY - STATE OF THE ART

The decision problem of selecting industrial process systems can be described as a complex and multi-objective task that is characterized by following aspects:

- The insufficiency or unavailability of vital information needed for decision making,
- The vagueness or uncertainty of the human knowledge in the field,
- The subjectivity of the decision makers,
- The reliability of the final results.

The core elements of the decision problem are objectives, attributes and alternatives. As attributes and alternatives increase, it becomes very hard for the human decision makers to analyse the relation between the attributes and alternatives and to arrive at a proper decision. For this reason, many techniques have been developed to support human experts in dealing with complex decision problems. Computer-aided decision support system has been introduced in many fields including business and services, research, medicine and engineering. In industrial application, decision support systems play an important role in process control, process trouble shooting or in selecting rational technologies and equipment for the manufacturing processes.

## 2.1 DECISION SUPPORT SYSTEM FOR PROCESS TECHOLOGIES AND EQUIPMENT SELECTION

The matter of rational selection of manufacturing technologies and equipment has been appreciated as deciding factor of the design and of the overall performance of manufacturing processes (Dağdeviren, 2008). In the manufacturing environment, making decision on process technologies and equipment selection encounter problems of incompatible criteria, imprecision, vagueness and uncertainty, and deals with a large number of economic and technical factors. To tackle the problem of incompatible criteria, techniques of MCDM have been developed, for example Simple Additive Weighting (SAW), Weighted Product (WP), Analytic Hierarchy Process (AHP), Technique for Order Preference by Similarity to Ideal Solution (TOPSIS), and Preference Ranking Organization METHod for Enrichment Evaluation (PROMETHEE). To cope with the vagueness and uncertainty of the available knowledge, fuzzy sets have been widely used instead of crisp sets. And to deal with the large amount of information to be processed, computer aided interventions have been successfully performed.

A large number of decision support systems for the selection of manufacturing processes has been introduced combining preceding three elements. The recent contributions in this field can be categorized as: AHP, combined AHP and TOPSIS, combined AHP and PROMETHEE, and rule-based knowledge system.

### 2.1.1 Analytic hierarchy process

Analytic hierarchy process (AHP) proposed by Thomas L. Satty (1987) has become one of the most prevalent techniques of multi-criteria decision making. In AHP, the decision problem is arranged in a hierarchical structure that allows a straightforward analysis of various technical and non-technical issues. Generally the AHP decision making procedure is accomplished in 3 steps (Cebeci & Kilinc, 2007; Durán & Aguilo, 2008):

- Define the goal and decompose the problem into a hierarchy structure of decision elements (goal, criteria, sub-criteria and alternatives)
- Employ pairwise comparison method and establish a reciprocal matrix, then calculate the weight vector
- Aggregate the relative weights of decision elements to obtain an overall rating for the alternatives and select the optimal one.

In defining the weight vector of the decision elements, the decision makers can use the concrete data about the elements or use their judgments about the relative importance of the elements. The AHP converts the evaluation to numerical values that can be compared and analysed along the hierarchical structure of the problem. In the later developments of AHP, fuzzy set theory initiated by Zadeh (1965) has been largely used. It allows converting the qualitative evaluation to the intervals or uncertain numbers (fuzzy number) rather than the exact numbers as in the classical AHP models. Fuzzy analytic hierarchy process has been found very useful to deal with the uncertainty and vagueness facing most decision making problems. Table 2-1 represents the recent applications of fuzzy AHP in the selection of process technologies and equipment.

Table 2-1. Applications of fuzzy AHP in process technologies and equipment selection

| ***Author*** | ***Area of application*** | ***Description*** |
|---|---|---|
| Durán and Aguilo (2008) | Advanced manufacturing technologies selection | Based on fuzzy linguistic reference relation.<br>Prototype software written on MATLAB 7.0. |
| Çimren et al. (2007) | Machine tool selection | Four main groups of criteria (productivity, flexibility, safety and environment, adaptability) and corresponding sub-criteria.<br>Cost analysis, reliability analysis and precision analysis are combined with the AHP-based methodology.<br>A computer program developed on Visual Basic. |
| Cebeci and Kilinc (2007) | Selecting Radio Frequency Identification (RFID) systems for glass industry | Three main criteria are investment factors, system characteristics, vendor criteria and corresponding sub-criteria.<br>Fuzzy linguistic variables are used to judge the selection criteria. |
| Chan et al. (2006) | Advanced manufacturing technologies selection | Decision criteria are classified into subjective criteria (flexibility, productivity, quality...) and objective criteria (economic factors)<br>Subjective criteria are evaluated by linguistic variables which later transformed into fuzzy numbers. Objective criteria are specified as triangular fuzzy numbers such as “the most pessimistic value”, “the most likely value”, “and the most optimistic value”.<br>Rankings of alternatives are obtained from normalization of geometric row means and a standard arithmetic method. |
| Shamsuzzaman et al. (2003) | Flexible manufacturing system selection | 14 criteria organized in 4 main groups including flexibility, cost, productivity and risk.<br>Fuzzy linguistic variables are employed to recognize the selection criteria.<br>The proposed methodology is implemented via an expert system named FmsExpertis written on Borland C++. |

The common reference criteria of the mentioned AHP systems are product quality, productivity, and economic efficiency. Energy considerations are rarely given in the appraisal of the priorities of the alternatives. The realized advantages of AHP in selecting technologies and equipment in manufacturing environment are: enable to capture both tangible and intangible aspects and both qualitative and quantitative data; effectively deal with inconsistency and complex decisions and unstructured problems; capable of handling multi-criteria and with the problems of uncertainty and imprecision (Chan et al., 2006; Durán & Aguilo, 2008).

### 2.1.2 Extended AHP

In the extended AHP developments, the rankings of alternatives calculated by the conventional AHP method will be double-checked for consistency or the proposed alternative will be measured the benefit in a real-time model.

Sun et al. (2001) studied a two-grade fuzzy synthesis decision making system using AHP for performance evaluation of grinding fluids. At the first grade, fuzzy ratings of each grinding fluid alternative versus a set of reference criteria are conventionally obtained with five different operating algorithms. The algorithm reliabilities are then evaluated and rated, and three operating algorithms with higher reliabilities will be used to aggregate the final scores of grinding fluid alternatives. This method is claimed to be advantageous in eliminating the subjective component of expert knowledge and improving the reliability of the results.

Another two-level AHP approach for the selection of rapid tooling process of injection mold was proposed by Nagahanumaiah (2008). At first, quality function deployment was incorporated with AHP pairwise comparison for mapping and rating the importance of the tooling processes based on a set of requirements. Fuzzy AHP method was subsequently used to access the design of the selected process in order to ensure the manufacturability and cost effectiveness of the rapid tooling mold. A feature-based computer program written in Visual C++ was developed to implement the proposed methodology.

Ayağ (2007) introduced an extended AHP system which uses AHP and process simulation together to support the selection of machine tools. AHP is firstly employed for weighting the machine tool alternatives. The alternatives weight higher than the suggested value of consistency will be then analysed using an automatically generated model of a real-life manufacturing system in order to measure their benefits for the entire system. The results will be compared and recommended for the final decision consideration.

It is noteworthy that in AHP the attributes where high values are preferred and the attributes where low values are preferred are often not easily distinguished. For example the performance of manufacturing equipment with respect to costs or risks are non-beneficial attributes and need to be distinguished by using negative references. However, using AHP they are not clearly identified. Correspondingly, a number of mathematic models was introduced to enable the evaluation of criteria of negative priority (Saaty, 2003) or even the new MCDM models were introduced to effectively tackle the opposite criteria problem. The TOPSIS (Technique for Order Preference by Similarity to Ideal Solution) and PROMETHEE (Preference Ranking Organization METHod for Enrichment Evaluation) were suggested in which criteria of positive and negative priorities were considered separately in the decision making process.

### 2.1.3 Combined AHP and TOPSIS

Technique for Order Preference by Similarity to Ideal Solution (TOPSIS) method was developed by Hwang and Yoon in 1981. The principle of this method is that a chosen alternative should be as close to the positive ideal solution and as far from the negative ideal solution as possible (Rao, 2007). The positive ideal solution is formed from a set of maximum attribute values that are predominantly exhibited by any alternative for each attribute, and the negative ideal solution is formed similarly from a set of minimum attribute values. The separation of each alternative from the ideal solution or negative ideal solution is measured by Euclidean distance.

TOPSIS method is more efficient in dealing with tangible attributes (Chakladar & Chakraborty, 2008; Ertyğrul & Karakaşoğlu, 2008), and provides better perception to decision makers by taking into account the differences and similarities of the alternatives according to the best and worst solution (Önüt et al., 2008). However, since TOPSIS does not provide a specific guideline for determining the relative importance of different attributes with respect to the overall objective, AHP has been integrated to give a comprehensive solution. The procedure of combined AHP and TOPSIS method is implemented as follows:

- Set up a decision matrix which presents the performance of all alternatives versus each criteria and normalize the matrix

- Determine the weights of all criteria with respect to the overall objective using the AHP method
- Aggregate the weighted normalized matrix which denotes the rating of each alternative with respect to the overall objective
- Obtain the positive ideal and negative ideal solutions
- Calculate the separation distance of each alternative from the ideal solution and negative ideal solution
- Calculate the relative closeness to the ideal solution and finally obtain the rankings of alternatives.

The combination of AHP and TOPSIS has been successfully applied for the selection of manufacturing technologies and equipment by Rao (2005), Chakladar and Chakraborty (2008), and Önüt et al. (2008). This combination was reported to enable a more scientific, consistent and meaningful investment decision.

### 2.1.4 Combined AHP and PROMETHEE

PROMETHEE (Preference Ranking Organization METHod for Enrichment Evaluation) is a multi-criteria decision making method developed by Brans and Vinkie in 1971. The implementation of PROMETHEE requires 2 additional types of information including information on the relative importance of considered criteria and information on the reference function for each separate criterion (Macharis et al., 2004; Dağdeviren, 2008). Whereas the relative importance of considered criteria has to be determined by the methods examined in the other studies, 6 types of preference function are available for comparing the contribution of the alternatives with respect to each criterion. These 2 types of information take part in the determination of outranking of alternatives in forms of partial ranking (PROMETHEE I) or complete ranking (PROMETHEE II) or Geometrical Analysis for Interactive Aid (GAIA). Similarly to TOPSIS method, since there is no specific guideline provided to determine the relative weighting of criteria in PROMETHEE, AHP is commonly used instead. In the combined AHP and PROMETHEE procedure, the concepts of positive and negative outranking flows were developed to deal with inverse reference attribute values. The procedure of PROMETHEE is summarized in a number of steps as follows:

- Define the problem and the objective, identify the alternative and criteria indicators
- Classify the criteria into direct category (performance have to be maximized) and in-direct category (performance have to be minimized) and assign the preference function for each criteria
- Assigning the relative importance of criteria using the AHP method.
- Form the performance matrix which presents the performance of all alternatives according to each criteria
- Compute the positive and negative outranking flows and the net flow for each alternative
- Obtain the pre-order of the alternatives following PROMETHEE I or PROMETHEE II

Integration of AHP into PROMETHEE helps overcome some shortcomings of PROMETHEE that have been reported in the literature, for example the uncertainty arises from the definition of criteria weights and assignment of criteria performance value of conventional PROMETHEE, or the unstructured figure (or black box approach) when dealing with a large number of alternatives (Macharis et al., 2004; Anand & Kodali, 2008). Such combination of AHP and PROMETHEE has been introduced in the literature for manufacturing technologies and equipment selection. Dağdeviren (2008) proposed a framework for selecting milling machines. The author assumed that it is possible to make better decisions if different PROMETHEE tools can be applied simultaneously. In detail, PROMETHEE I identifies the incomparable and indifferent alternatives by making partial ranking while PROMETHEE II provides the complete rankings of alternatives and the GAIA helps to figure out useful information that might have been lost during the ranking process.

### 2.1.5 Rule-based expert system

A totally different approach is based on a system of rules and expert knowledge, known as rule-based expert system. Unlike the aforementioned multi-criteria decision making techniques that provide the ranking for the given solutions according to a set of reference criteria, a rule-based expert system provides solutions inferred from a well-structured set of facts and rules. A typical rule-based system consists of two basic components: The knowledge base containing the domain knowledge useful for problem solving, the reference engine to carry out the reasoning and derive solutions as response to user's queries. The expert knowledge is collected and encoded in a set of IF-THEN production rules. The user provides facts as input information to the system and receives expert advices in response.

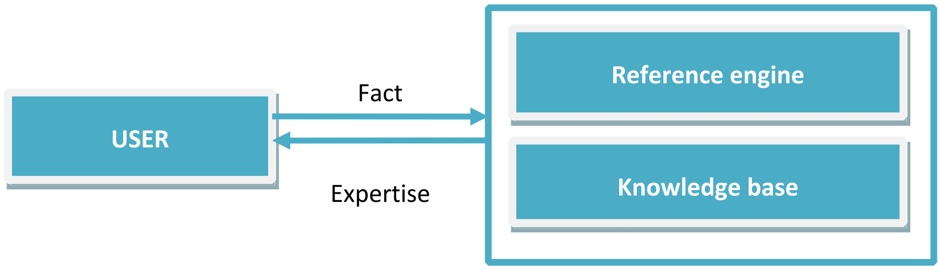


Figure 2-1. Principle structure of a rule-based expert system

Numerous rule-based expert systems have been developed for supporting the selection of manufacturing technologies and equipment. Several of them have been mentioned hereinafter in this study.

Edalew et al. (2001) studied a rule-based expert system for the automatic selection of cutting tools and optimizing cutting conditions. The system comprises several components: the knowledge acquisition module, the knowledge base module, the inference engine, the user interface and the database. The rules for selecting cutting tool are divided into 4 groups associated with the tool material selection, cutting type and feature specification, machining technique selection and cost estimation, cutting tool selection and optimum cutting parameters. They are linked to the stages in the proposed analysis procedure. The user has to provide information about the tool material (component status, material type, mechanical properties, thermal properties, cutting temperature), feature's type, targeted cost and manufacturing, then receives a best set of cutting tools, optimum cutting parameters and machining time and cost estimation as response.

In the rule-based expert system for selecting cast components (Er & Dias, 2000), the selection parameters are structured in five interconnecting levels. The first level is for selecting the suitable casting processes against the user's design specifications while the final level is for recommending the most suitable economical process. The casting expert domain is presented as IF-THEN rule and the selection is processed as all the rules in the knowledge base are evaluated until all the possible outcomes are analysed.

In a development by Barua and Sengupta (1996), the selection of sensors to measure the process variables also relies on a rule-based approach. The system works with 12 process variables and consists of 94 rules in its knowledge-base; each rule is enriched with a large number of attributes. The system results in the sensor recommended for the chosen process variables.

Lababidi and Baker (2003) described the design and implementation of an integrated web-based fuzzy expert system for food dryer selection, known as Dryer Selection Expert System (DrySES). The selection process involves 6 main steps: 1. drawing up the process specification; 2. making preliminary selection; 3. planning and conducting bench-scale tests; 4. making an economic comparison of alternatives; 5. conducting pilot-scale trials, and 6. selecting the most appropriate dryer type. The knowledge base contains several sets of rules concerning drying mode (batch or continuous dryer), dryer operation (freeze, vacuum or atmospheric dryer operation), feed class (solid, paste or slurry), dryer type (recommending the most suitable type of dryer based on the three earlier decisions), single/multiple (single or multiple batch dryers) and heating mode (indirect heating of inlet air or a direct-fired heater). The DrySES consists of independent modules including KCommon, KBatch, KContinuous, and KSpray for the technical selection of appropriate dryer and some “foreign” programs for providing additional information for the selection process.

The rule-based expert systems exhibit the characteristics of logical and symbolic reasoning, high-quality performance, explanation capability and acceptability of fuzzy data and inexact reasoning. These characteristics are very useful for solving the problem of manufacturing equipment selection. However, it is worth noting that knowledge engineering for manufacturing decision support requires significant time and effort and that rule-based expert systems can work well only within a narrow domain of knowledge. On the other hand, the rule-based method is rather inflexible with regard to the fixed reference attributes that have been predefined during the knowledge engineering process.

## 2.2 DRYING PROCESS SELECTION

Drying is an important unit operation for many industrial sectors. More than 200 different dryer types have been developed and commercialized for various manufacturing processes such as food, paper, textile, chemical, pharmaceutical products, and so forth (Mujumdar, 1997). Drying is, on the other hand, an energy-intensive operation that is responsible for up to 15% of all industrial energy usage, often with relatively low thermal efficiency in the range of 25-50% (Chua et al., 2001). However, the selection of industrial dryers is a complex process due to the fact that there exists a great diversity of drying technologies and each of these technology types has a wide assortment of sub-categories. A reliable dryer selection decision should rely on many aspects such as the process specifications, final product quality, economic efficiency, and safety and environmental considerations (Crapiste & Rotstein, 1997), such as the availability of energy in a suitable form (Heß, 1984).

A growing number of studies (Land, 1991; McMinn, 1999; Lababidi & Baker, 1999, 2003; Vega-Mercado et al., 2001; Mujumdar & Devahastin, 2003; Crapiste & Rotstein, 1997) provides decision support for dryer selection in various forms including flowcharts, guidelines, procedures, checklists, decision trees, case studies and computer-aided expert systems. Most of the reports recommend dryer selection on the consideration of factors such as dryer throughput, moisture content of wet feed and desired product, physical properties of the feed and product, upstream and downstream processing operations, quality of dried product, economic performance of drying systems, amongst others. It needs to be noted that the above selection methods basically rely on data mining techniques to draw advisable drying equipment for given conditions.

According to a survey by SPIN[3] in 2000, there is a need for user-friendly expert systems and better standardization to assist with this complex selection process (Jangam & Mujumdar, 2010). However, a very limited number of computer-aided expert systems for dryer selections have been developed so far. Reviews given by Baker and Lababidi (2001), Saravacos and Kostaropoulou (2002), and Kemp et al. (2004; 2007) revealed only five major developments in

[3]SPIN: Solids Processing Industrial Network, founded by 14 large chemical companies that are based in Europe

this field: the Dryer Selection Expert System (DrySES) introduced by Lambabidi and Baker (1999, 2003; 2000); the Expert system for Dryer Selection (DrySel) introduced by Kemp et al. (2004; 2007); the intelligent information system for the selection and calculation of drying equipment (DryInf) (Matashov et al., 1998); the DSS for selecting appropriate equipment and conditions for drying cereal grains (Weres et al., 2010), and the database system for drying process (BANID). The first two developments are both fuzzy rule-based approaches, where the selection is processed based on the input data of feed material properties, overall flow sheet and drying equipment specifications. In DryInf, the dryer selection is based on a comprehensive analysis of material properties and requirements for production including capacity, max and min diameter of particles, type of moisture, aggregation state, adhesiveness, cohesiveness etc. Another approach, BANID, is simply a database system which provides information related to the drying processes including software and models, equipment and technologies, control methods and environmental and safety aspects. Table 2-2 provides more details of these developments.

Table 2-2. Review of major developments of expert system for dryer selection

| *Expert system* | *System component* | *Data input* | *Selection process* | *Reference* |
|---|---|---|---|---|
| Expert system for Dryer Selection - DrySel | Fuzzy rule-based expert system<br><br>Five-step algorithms based on the material and flow sheet consideration, using merit score to compare dryers. | Equipment specification (mode of operation, heating, feeding)<br><br>Material (hard, sticky)<br><br>Overall flow sheet (material flow rate, moisture content) | Define data input<br><br>Make basic choice of heating types, operation mode<br><br>Evaluate merit factors for individual types of drying equipment<br><br>Study sub-types and special features of dryer and flow sheet<br><br>Make the final evaluation based on suitability and cost. | Kemp et al. (2004), Kemp (2007) |
| Dryer Selection Expert System - DrySES | Fuzzy rule-based expert system<br><br>Four separate knowledge modules :<br><br>- Testing the appropriate operation mode,<br><br>- Selecting dryers of batch mode<br><br>- Selecting dryer of continuous mode | - | Define dryer specifications<br><br>Perform preliminary dryer selection<br><br>Conduct bench-scale drying tests<br><br>Make economic comparison of alternatives<br><br>Conduct final pilot-scale tests<br><br>Define the most appropriate dryer | Lababidi and Baker (1999, 2003) |

| *Expert system* | *System component* | *Data input* | *Selection process* | *Reference* |
|---|---|---|---|---|
| | - Selecting spray dryer | | type | |
| Intelligent information system for the selection and calculation of drying equipment - DryInf | System's database including: material properties, drying equipment, dryer domestic and foreign producers.<br>Expert system for dryer selection<br>Economic evaluation module<br>Simulation module with object-oriented programming | Dryer capacity<br>Particle aggregation, particle diameter (max, min), particle size distribution<br>Maximum material temperature<br>Type of moisture<br>Cohesive, dustabilty, explosive, flamability… | Pre-selection of drying equipment.<br>Evaluation of economic effectiveness of selected drying equipment<br>Simulation of drying equipment (only spray drying) | Saravacos and Kostaropoulou (2002) |
| Web-based DSS for designing and managing cereal grain drying and storage | 3 components:<br>- Databases for cereal grain drying,<br>- Simulation and performance analysis<br>- Decision support for selecting appropriate equipment and conditions for drying cereal grains | Performance of dryer<br>Prediction of drying<br>Air properties<br>Equilibrium moisture content<br>Air flow resistance | Provide advises to farmers in their decisions concerning the selection of appropriate equipment and conditions for drying cereal grains | Weres et al. (2010) |

| ***Expert system*** | ***System component*** | ***Data input*** | ***Selection process*** | ***Reference*** |
|---|---|---|---|---|
| Database system for drying process - BANID | 4 sub-databases:<br>- Drying software and selected models;<br>- Drying equipment and technologies;<br>- Drying control methods including sensors;<br>- Environmental and safety aspects | | This database system provides ability to search the required information of selected dryer types | Saravacos and Kostaropoulou (2002) |

Rule-based approaches using fuzzy logic have been found the most promising solution for a decision-aided dryer selection. In most of the aforementioned systems, the final decision is supported by the numerical scores, presenting the measurement of advisability of the dryer types. Basing the calculations of the numerical scores on the fuzzy numbers, the results may lead to major errors due to cumulative fuzziness. Clear-cut distinction can only be drawn if the merit scores are substantially different. On the other hand, dryer selection problems are very specific and no rigorous algorithm can be used. It is noteworthy that the numerical score calculations are mainly based on the technical evaluations rather than the systematic consideration of environmental, social and economic performances of the equipment. Besides, programming of a rule-based expert system for dryer selection actually requires great effort due to the wide categorization of dryer types and the sophistication of the drying process.

## 2.3 CHAPTER FINDINGS

Although a large number of multiple criteria decision making (MCDM) methods have been developed in the field of decision support in manufacturing environment, analytic hierarchy process (AHP) remains the most widely applied method in practice. Other well-known MCDM techniques, on the other hand, are principally based on the extension of AHP in which the relative weightings of attributes are determined by pairwise comparison technique. In addition, the fuzzy set theory has been found the appropriate solution to deal with the ambiguity and uncertainty facing in many MCDM problems.

The combination of AHP and fuzzy logic has been proven to provide a promising theoretical framework for the selection of industrial process technologies. Nevertheless, most of the aforementioned MCDM methods work well if there are only several alternatives to choose from. The increase in the number of attributes may cause the system to be more cumbersome and the results to become less accurate.

Another approach, the rule-based techniques, basically rely on data mining techniques to draw advisable solutions for the given conditions rather than the rating and ranking procedure of the MCDM approach. Thanks to the characteristic of logical and symbolic reasoning, high-quality performance, explanation capability, rule-based expert system has been found widespread application in industrial practices.

The selection of industrial drying technologies is actually a very complex process. However, a very limited number of expert systems has been developed for dryer selection. Most of them are based on rule-based technique and fuzzy logic. The final decision is supported by the numerical scores, presenting the measurement of advisability of the dryer types.

It is worth to stress that the cumulative fuzziness will increase with the increase of algorithms in the calculation of the merit scores. This may cause major errors in the results obtained. The abovementioned developments are mainly based on the technical evaluations rather than the systematic consideration of environmental, social and economic performances of the equipment. Furthermore, most of the developments reported in the literature are from quite long ago. The DrySES and DryInf cannot be found in practice so far. Only the DrySel is still in use and commercialized by the Aspen Technology Group.

In brief, developments of expert systems for dryer selection are still quite unsatisfying and insufficient. Accordingly, there is a need for user-friendly and better-designed/reliable expert systems to assist with this complex selection process.

# 3. THE PROPOSED FRAMEWORK

In this study, a specific combination of rule-based technique and fuzzy analytic hierarchy process was examined for the development of an integrative framework for selecting thermal process technologies. The selection process consists of two steps and results in the ranking of possible thermal process technologies for a particular product. The goal is to provide decision support at the early stage of selecting appropriate technologies considering sustainability for thermal food processes.

## 3.1 AN INTEGRATIVE APPROACH

Dealing with multi-criteria decision making (MCDM), the proposed decision support framework is structured from the combination of three methods: rule-based technique, fuzzy logic and analytic hierarchy process.

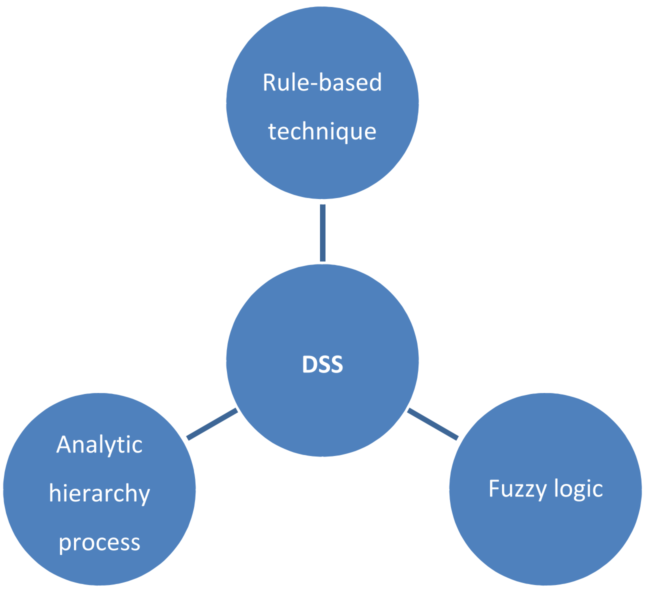


Figure 3-1. The integrative approach

Each individual method has been widely applied in engineering. However, combination of these 3 methods is a new approach of decision support system in process selection. The selection procedure comprises two main steps: the preliminary selection step and the final selection step. The preliminary selection narrows the range of thermal process technologies suitable for the product under consideration. The final selection provides the ratings of technologies within the predefined range according to a set of appropriate criteria.

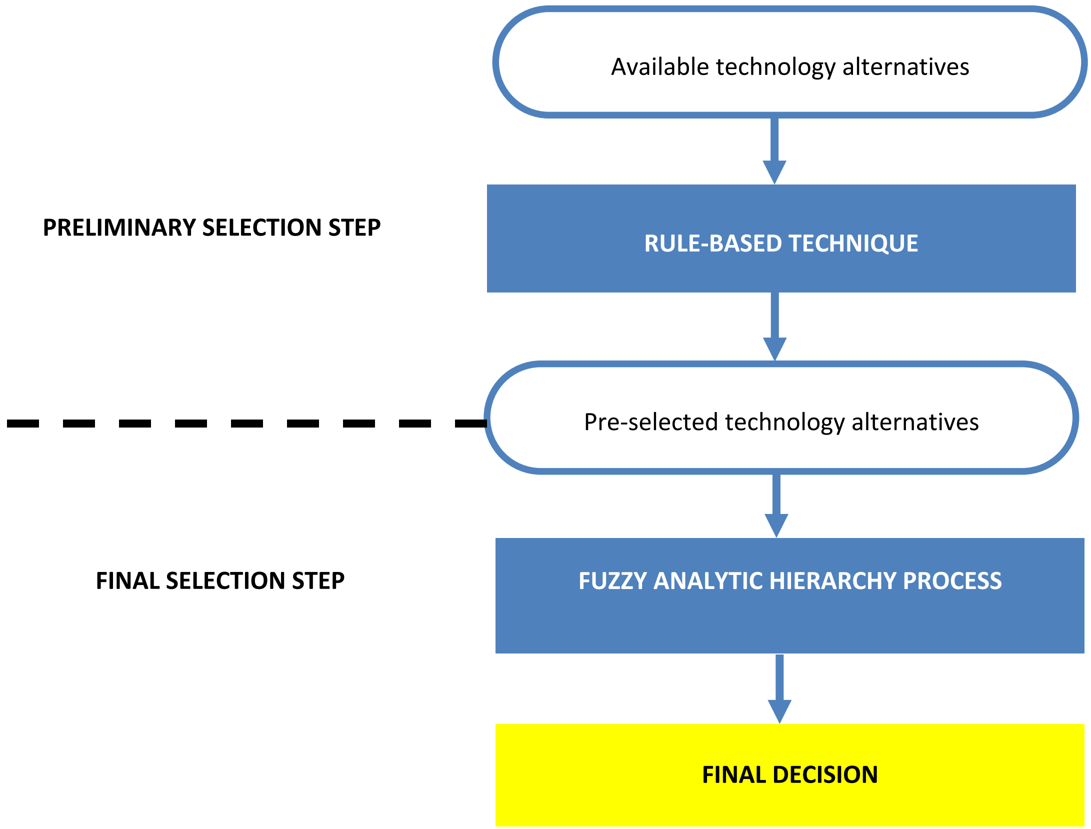


Figure 3-2. The proposed MCDM framework

The proposed integrative framework provides decision support for two different applications:

- Selecting new facilities
- Upgrading or changing the used technologies of the existing facilities.

Hereinafter, the development of this integrative framework will be presented step-by-step.

## 3.2 SUBDIVISION OF THE THERMAL PROCESS SYSTEM

In this study, it is suggested to subdivide the thermal process system into three subsystems following the sequence of energy flow in the process:

- Heating subsystem: converting energy primary type (fossil fuel, electric, biomass or solar energy) to secondary energy (steam, hot air, hot water…) which will be utilized in the process.
- Processing subsystem: preparing and processing of materials using thermal energy supplied by the heating subsystem.
- Heat recovery subsystem: recovery of a part or entire exhaust thermal energy into the process.

This subdivision can ensure to:

- Cover a wide range of technologies available on the market;
- Facilitate the rule-based selection;
- Facilitate the comprehensive evaluation of environmental performance, economic performance and social performance.

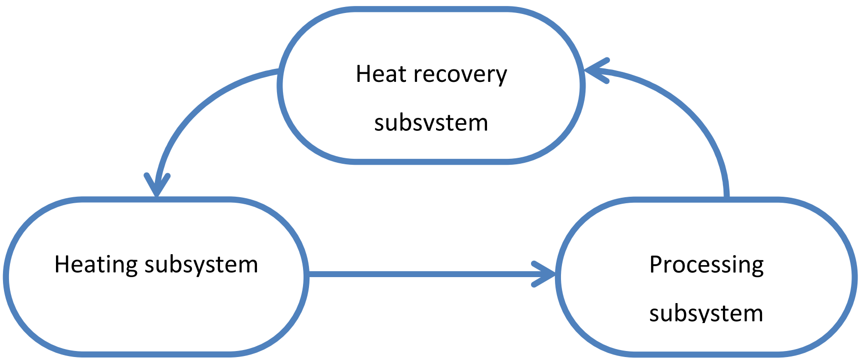


Figure 3-3. Subdivision of the thermal food process system

The processing subsystem is representative for the whole system due to the fact that it is the most critical operation for most thermal processes.

Each subsystem is characterized by a set of classification indicators. In Table 3-1, the three subsystems and some common classification indicators are correspondingly presented.

Table 3-1. Common classification indicators of the thermal process subsystems

| ***Subsystem*** | ***Classification indicator*** | ***Type*** |
|---|---|---|
| Heating subsystem | Heating type | Convection, radiation, conduction, magnetic fields, combinations of different types |
| | Heating medium | Direct fire, saturated/ superheated steam, solar energy, hot air/flue gas |
| | Primary energy type | Fossil fuel, Biomass, Electric, Solar |
| | Heating supply method | Electric heater, steam boiler, hot air boiler, solar collector, heat pump |
| | Vacuum system | Vacuum pump and condenser |
| Processing subsystem | Operation mode | Batch, continuous |
| | Operation temperature | Below boiling point, at boiling point, above boiling point, below freezing point |
| | Operation pressure | Vacuum, atmospheric pressure, high pressure |
| | Relative motion | Co-current, counter current, cross current, mixed flow |
| | State of material in the process | Stationary, moving, agitation, fluidization, vibration, |
| Heat recovery subsystem | Recovery of waste heat stream | Venting (no recovery), recirculation damper, heat pump dehumidifier, heat wheel, heat pipe, run-around coil heat |

| *Subsystem* | *Classification indicator* | *Type* |
|---|---|---|
| | | exchanger, plate heat exchanger, two section heat exchanger, scrubber condenser, vapour condenser, vapour re-compressor |

Technologies of the whole thermal process system (hereinafter, "system") are configured from the appropriate combinations of the technologies of the modular subsystems (hereinafter, "subsystem") (see Figure 4-7).

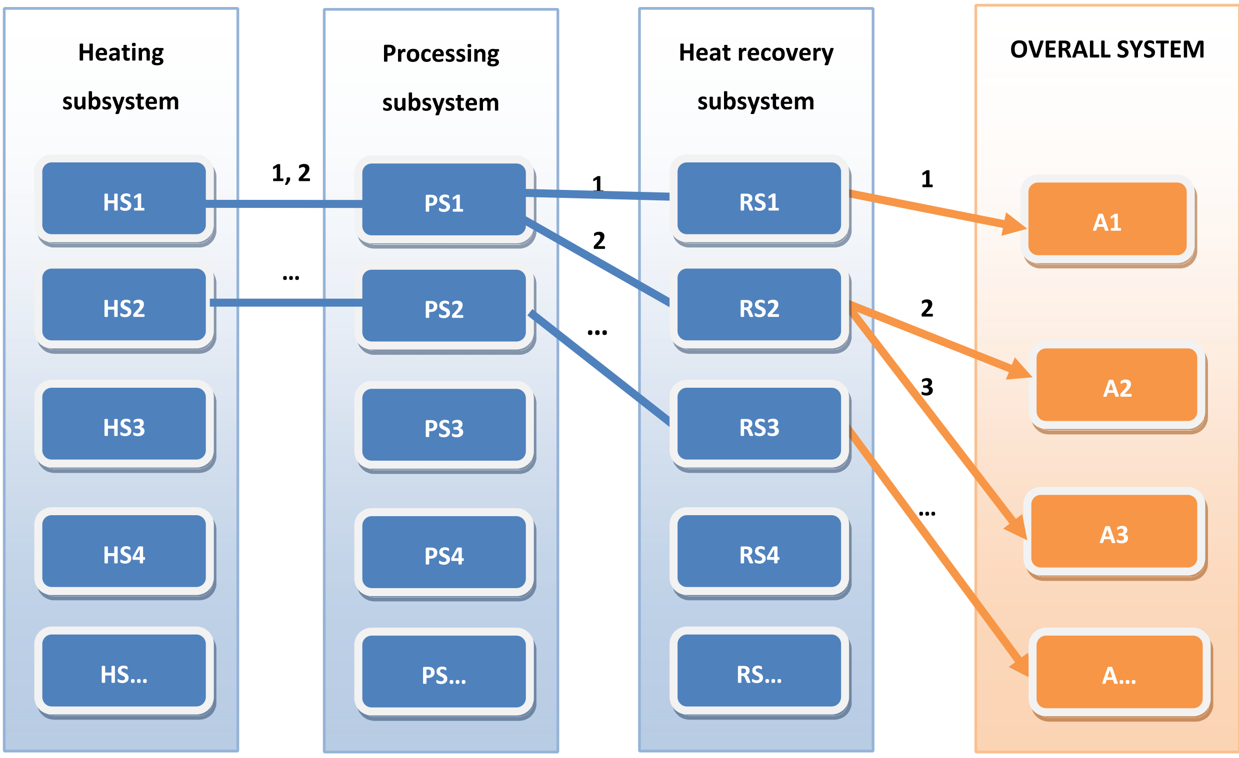


Figure 3-4. Illustration of the configuration of technologies of the overall thermal food process

The proposed integrative framework for the selection of subsystem technologies and overall system technologies based on this subdivision is demonstrated in Figure 3-5.

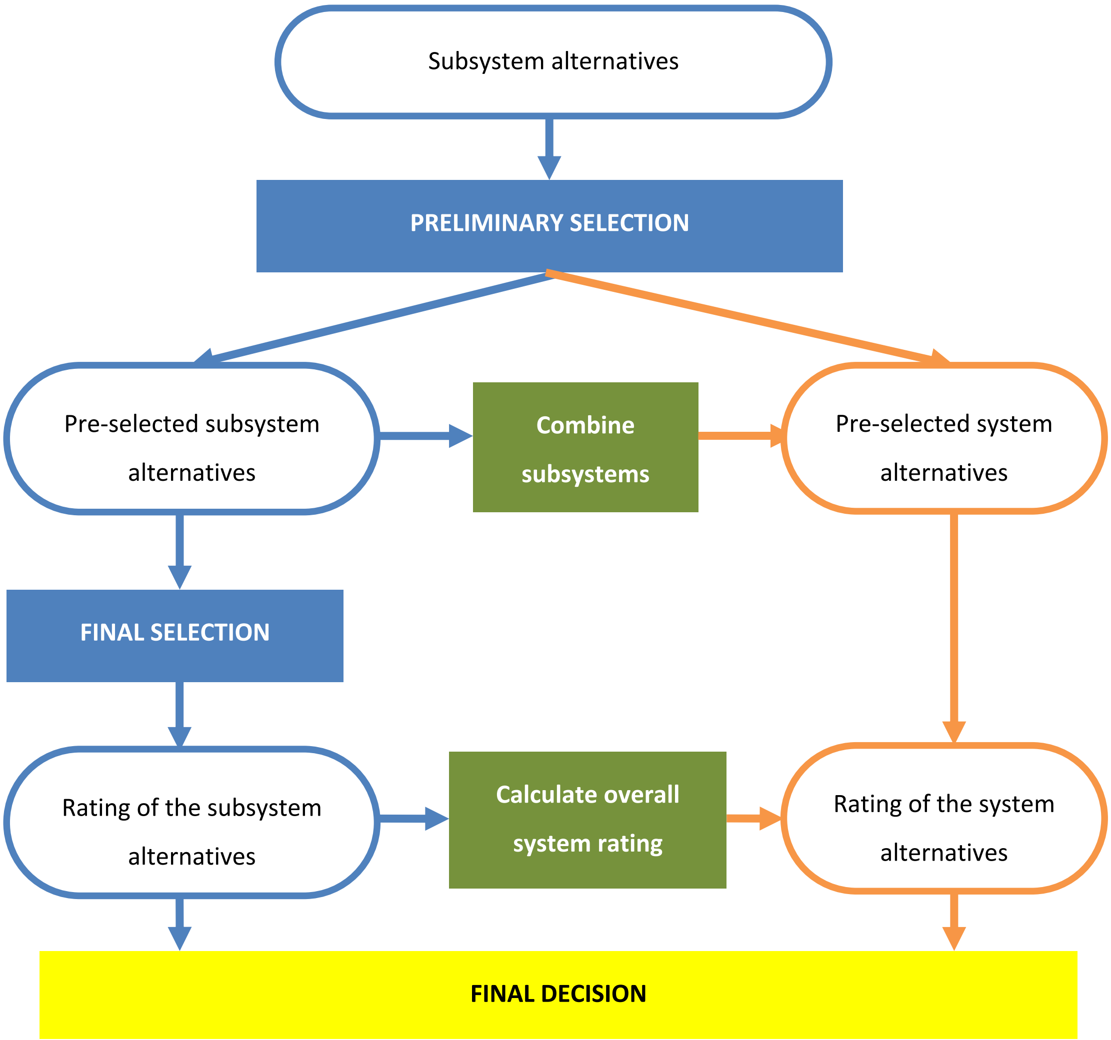


Figure 3-5. System subdivision in the selection process

## 3.3 PRELIMINARY SELECTION STEP

In the preliminary selection step, rule-based technique has been applied. This is not a step-by-step process. The selection relies on the technical specifications of the technologies and the food products. The system is made up of two basic components including the database and the rule-base.

### 3.3.1 The system database

There will be three interactive databases concerning the thermal process technologies (technology database), the food materials and products (product database) and the capability of the technologies and the products (capability database).

**Technology database**

The technology database contains data of the technologies available for the thermal processes and their technical specifications with respect to the classification indicators. It comprises three separate groups of data concerning the abovementioned subsystems and the other group containing the overall system technologies which are configured from the appropriate combination of the modular subsystem technologies. In so doing, the database can cover a wide range of process technologies but still ensure the detailed specification of the individual part of the system.

**Product database**

The product database contains the technical specifications of a wide range of food products undergone the corresponding thermal processes. The categorization of the food products is defined basically in accordance with the NACE code; sub-sector DA15.3 - Production of food and vegetable products.

In the product database, the technical specifications of the products are related to both the preliminary selection and the final selection processes. For the preliminary selection purpose, the data include the common technical characteristics of the substances to be processed, for example the physical form of feed and product, the basic requirement of product, the allowable process temperature, etc. For the final selection purpose, the data necessary for the appraisal of process sustainability are given.

**Capability database**

The capability database contains the domain of expertise on the capability of the subsystem technologies with respect to each attribute of the technical specification of the products. Thus, there will be three capability expert domains regarding the three subsystems in the process.

### 3.3.2 The rule-base

The rule-base is for implementing the selection. For a particular product, the subsystem technologies will be selected if they are capable of all technical specifications of that product. The selection is carried out by a set of production rules, presented in the form of IF-THEN rule.

In general, the selection of the subsystem technology (T) for a given product P which is characterized by a set of specifications ($p_1$, $p_2$, ..., $p_n$) is as follows:

IF <T is capable of $p_1$>

AND <T is capable of $p_{...}$>

AND <T is capable of $p_2$>

AND <T is capable of $p_n$>

THEN <select T>

As a result, a number of technologies will be selected for each of the three subsystems. The pre-selected systems will be then configured from the combination of the pre-selected technologies of the modular subsystems.

## 3.4 FINAL SELECTION STEP

In the final selection step, the subsystem technologies selected in the first step are rated and ranked using fuzzy analytic hierarchy process technique.

### 3.4.1 Hierarchical criteria system

The proposed hierarchical criteria system is organized in 4 levels, existing of several constituents as detailed in Figure 3-6.

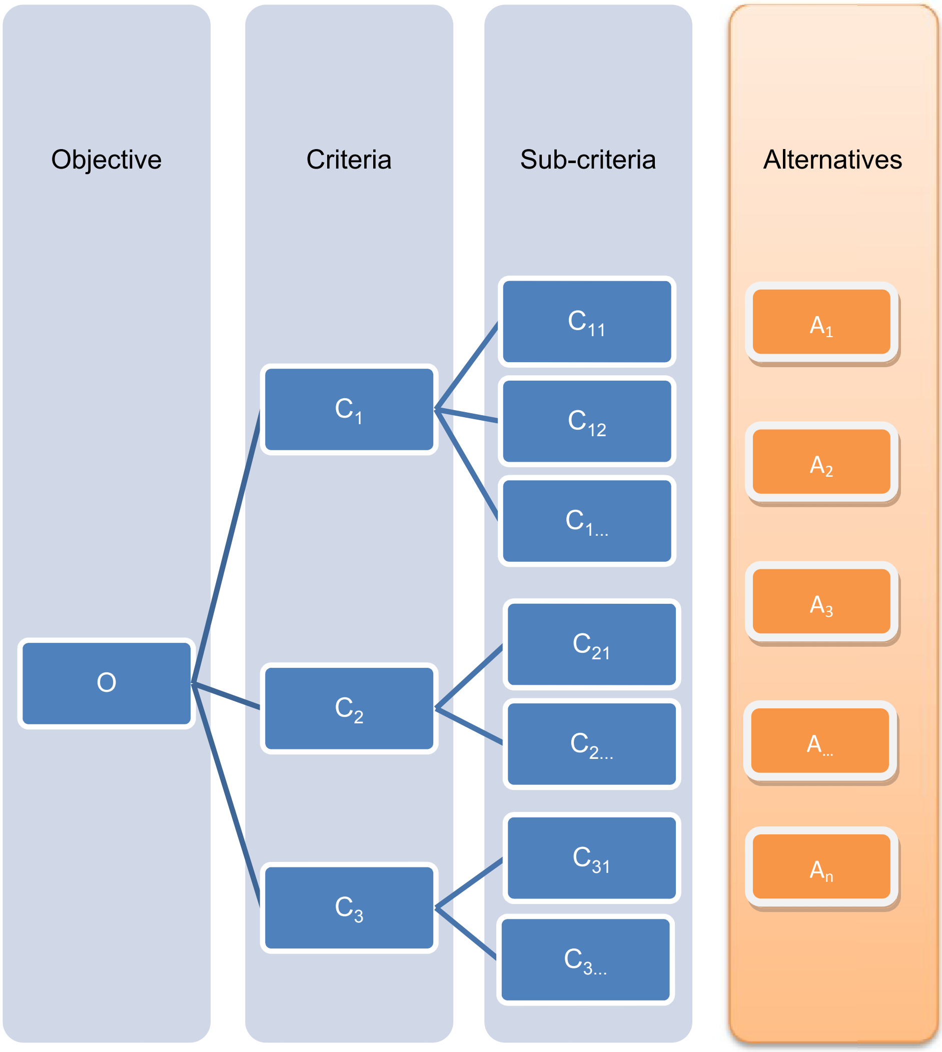


Figure 3-6. The hierarchical criteria system

Considering the sustainability of the process, the evaluation and selection of thermal food processes should be based upon three main criteria: environmental, economic, and social performances (Figure 3-7). Each criterion is broken down into sub-criteria which are supposed to be dependent on the thermal processes. Table 3-2 shows the sub-criteria commonly considered in the evaluation of the thermal food processes.

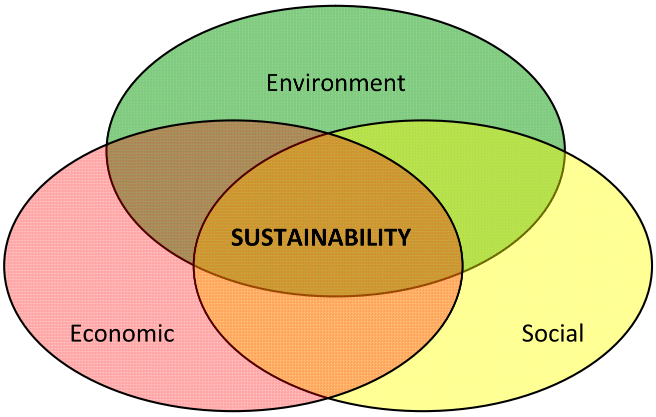


Figure 3-7. Selection criteria considering sustainability

Table 3-2. Overview of the main criteria and corresponding sub-criteria for the selection of thermal food processes

| ***Criteria*** | ***Sub-criteria*** |
|---|---|
| Environmental performance | Energy performance (energy consumption, energy efficiency, renewable energy usage, energy recovery)<br>Environmental impacts (greenhouse gas emission, waste water discharge, solid waste discharge) |
| Economic performance | Initial investment cost, operation cost, net present value, benefit-cost ratio, payback period |
| Social performance | Product quality, hazards, space requirement, processing time, convenience |

Here, the reference criteria are distinguished as to positive attributes and negative attributes to facilitate the application of appropriate algorithms for the weighting and rating process.

### 3.4.2 Rating and ranking of the subsystems

The rating and ranking procedure is illustrated in Figure 3-8 below.

First, justification for constituents at different levels in the hierarchy is defined using absolute justification and comparative justification. The justification can be in the form of qualitative judgment or quantitative judgment and will be expressed in triangular fuzzy numbers. In the normalization step, the judgment data is converted to dimensionless values, which represent the local weight of constituents in each level of the hierarchy. Next, weightings of the alternatives are aggregated step-by-step along the hierarchy. The result of this step is the global weight $R_i$ of the alternative $A_i$ with respect to the overall objective O of the system.

After this step, the ratings of the subsystem alternatives (value $R_i$) are still in the form of fuzzy numbers, which are not easy to compare and therefore it is not easy to determine the more preferable one. For this reason, it has to be defuzzified and converted to crisp numbers in the final step.

The more detailed description of these steps is given in the following paragraphs.

This calculation process is repeated for each of the three subsystems. As a result, there are three separate ranking lists for the three subsystems. Since the processing subsystem is the core component of the thermal process, its ranking should be representative for the whole system and should be considered first. Selection of heating technology and heat recovery technology should be subsequently considered.

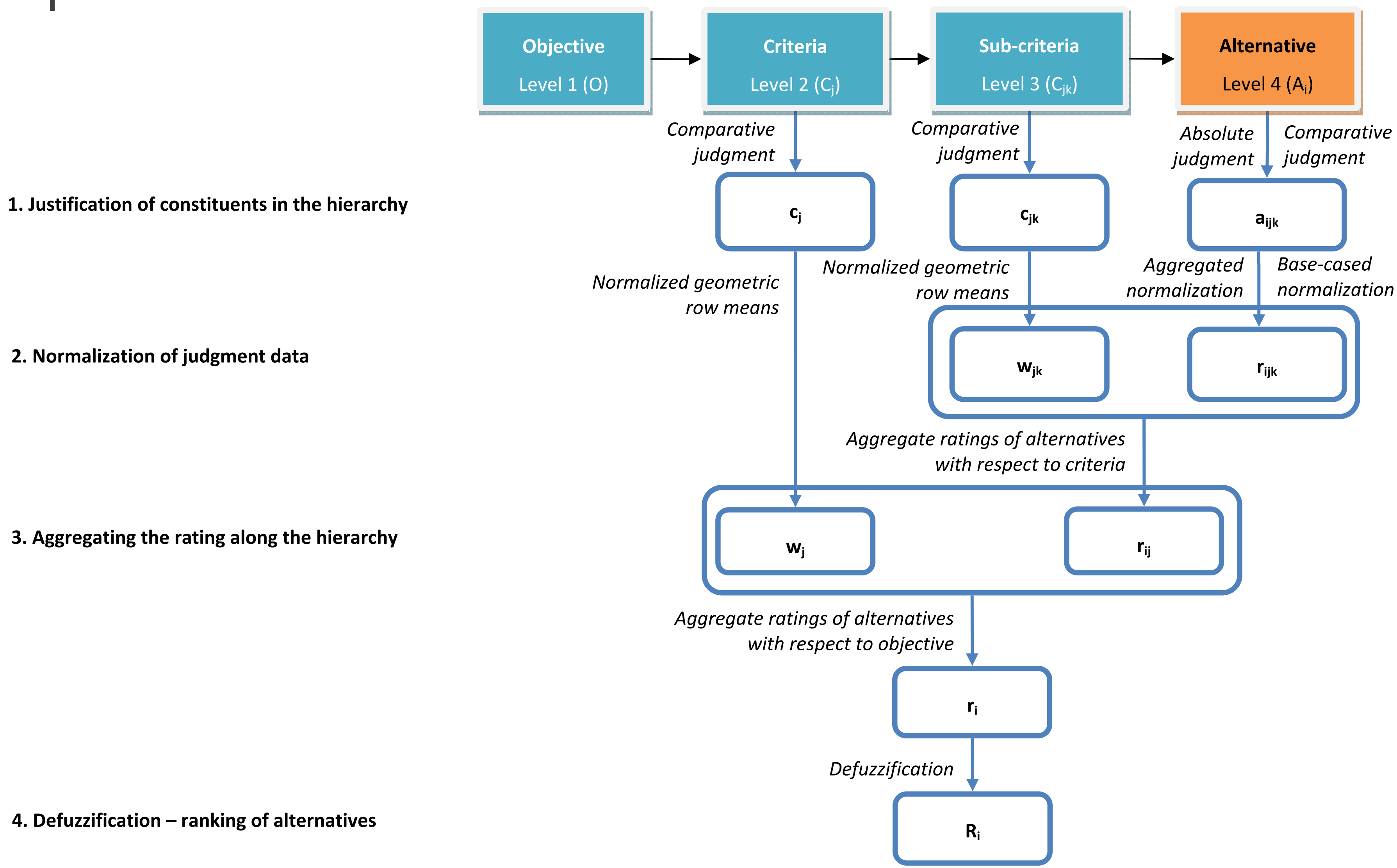


Figure 3-8. Rating and ranking procedure

#### 3.4.2.1 Justification of constituents in the hierarchy

First, justification for constituents at different levels in the hierarchy is defined. Here, two methods are proposed for assigning the justification: absolute justification and comparative justification.

**Absolute justification**

In the case of absolute justification, preferences of constituents are interpreted regarding their real performance. It is proposed for the justification of thermal process technologies against the sub-criteria in the hierarchy (level 4 against level 3 respectively). Absolute justification can be in the form of quantitative judgment or qualitative judgment. Quantitative judgment is only applied for the justification of alternatives with respect to the sub-criteria of energy performance. Qualitative judgment is applied for the justification of the alternatives with respect to the sub-criteria of economic and environmental performances.

**Comparative justification**

Comparative justification describes the relative preference of each constituent compared to the others in a given set of constituents. It is used to evaluate the importance of the constituents at level 2 (sub-criteria) and the level 3 (criteria) in the hierarchy using pair wise comparison technique, and is specified in reciprocal matrix as described in Chan et al. (2006). Comparative judgment is also represented in form of triangular fuzzy numbers, using qualitative judgment to deal with the vague and uncertain information.

For each given set of constituents, a reciprocal judgment matrix will be constructed in which the constituents are distributed along both axes (Table 3-3). Each element of the matrix expresses the relative importance of the constituents along horizontal axis to the one along vertical axis.

The elements of the fuzzy reciprocal matrix are such that products of each upper triangle element with its corresponding lower triangle element should be approximately equal to one.

Table 3-3. An example of fuzzy reciprocal matrix

| ***Criteria*** | ***C1*** | ***C2*** | ***C3*** | ***…*** | ***Cn*** |
|---|---|---|---|---|---|
| **C1** | EQ | H | H | M | M |
| **C2** | | EQ | M | H | L |
| **C3** | | | EQ | H | L |
| **…** | | | | EQ | VL |
| **Cn** | | | | | EQ |

Table 3-4 gives an overview of constituents and justification at all levels of the hierarchy.

Table 3-4. Overview of constituents in the hierarchical criteria system

| ***Level*** | ***Constituent*** | ***Denotation*** | ***Justification*** | ***Justification method*** |
|---|---|---|---|---|
| 4 | Alternatives | $A(A_1,A_2,A_i,\ldots,A_n)$ | Evaluation of constituents of level 4 ($A_i$) versus constituent of level 3 ($C_{jk}$) | Absolute judgment |
| 3 | Sub-criteria | $C_{jk}(C_{j1},C_{j2},C_{jk},\ldots,C_{jp})$ | Evaluation of constituents of level 3 ($C_{jk}$) versus constituent of level 2 ($C_j$) | Comparative judgment |
| 2 | Criteria | $C_j(C_1,C_2,C_j,\ldots,C_m)$ | Evaluation of constituents of level 2 ($C_j$) versus the overall objective | Comparative judgment |
| 1 | Objective | O | Overall objective of the system | |

**Fuzzy number representation of the judgment data**

Most of the decision making processes rely on a huge amount of data that may be unobtainable or available with vagueness. In order to deal with such insufficiency and uncertainty, in this study, the data is generally specified in triangular fuzzy number (TFN). Definition and arithmetic operations of triangular fuzzy numbers can be easily found in literature (Lee, 2005; Siler & Buckley, 2005).

As described before, the judgment data is presented in two forms: quantitative judgment and qualitative judgment. Triangular fuzzy numbers of the quantitative judgment are presented as the lower bound value (LBV), most occurring value (MOV) and upper bound value (UBV) within the range of the available data as shown in Figure 3-9.

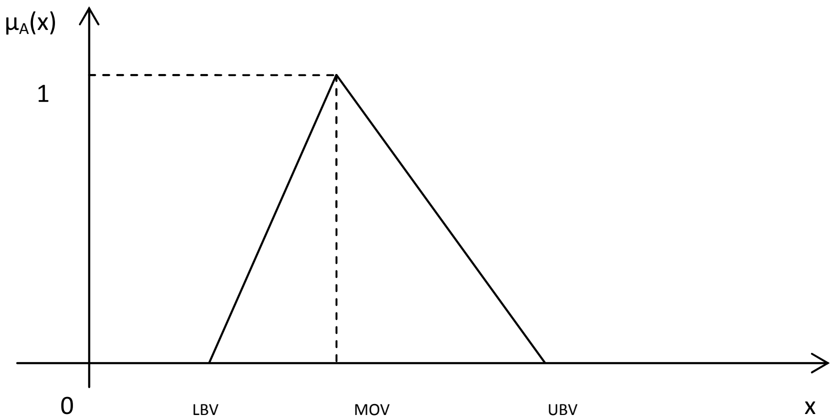


Figure 3-9. Triangular fuzzy number for quantitative judgment

Qualitative judgment is applied for constituents where reliable quantitative measurement is not possible. A proper linguistic scale and triangular fuzzy scale presented by Chan et al. (2000) have been applied in this study as demonstrated in Table 3-5 and Figure 3-10.

Table 3-5. Linguistic scale and TFN conversion scale of qualitative judgment

| ***Verbal term*** | ***Linguistic scale*** | ***Triangular fuzzy scale*** |
|---|---|---|
| Very high | VH | (3, 5, 5) |
| High | H | (1, 3, 5) |
| Medium | M | $(\frac{1}{3}, 1, 3)$ |
| Exactly equal | EQ | (1, 1, 1) |
| Low | L | $(\frac{1}{5}, \frac{1}{3}, 1)$ |
| Very low | VL | $(\frac{1}{5}, \frac{1}{5}, \frac{1}{3})$ |

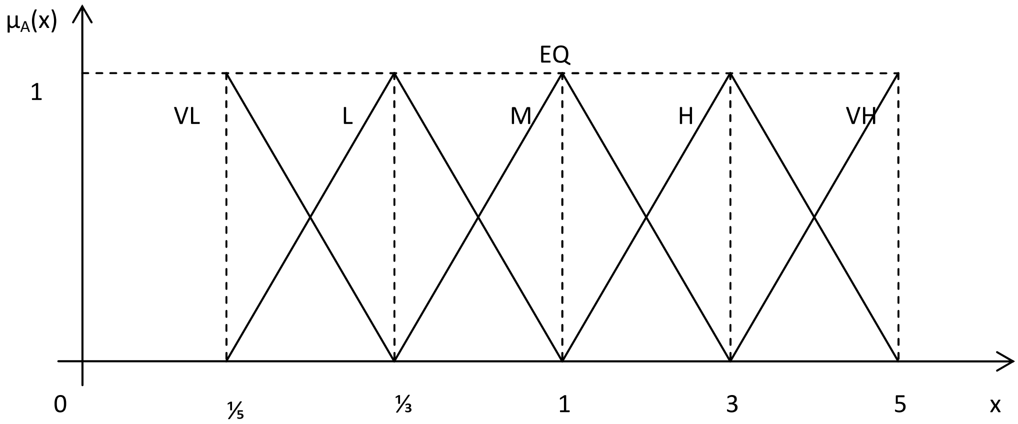


Figure 3-10. Membership function for qualitative judgment

3.4.2.2 Normalization of judgment data

The justifications of constituents are then transformed to relative weighting values by normalization. Normalization converts judgment data to dimensionless values and ensures the compatibility between absolute justification and comparative justification and between quantitative judgment and qualitative judgment. This can also be interpreted as the local weight of the constituents, meaning the weight with respect to the constituent at the upper level in the hierarchy.

Local weight of constituents at level 2 and level 3 (comparative justification) is defined by geometric row mean method as follows:

$$g_{jk} = \left( \frac{c_{jk1} \oplus c_{jk2} \oplus \dots \oplus c_{jkl} \oplus \dots \oplus c_{jkp}}{p} \right) \quad 3\text{-}1$$

$$w_{jk} = g_{jk} \oslash \left( \frac{g_{jk} \oplus g_{jk} \oplus \dots \oplus g_{jk} \oplus \dots \oplus g_{jp}}{p} \right) \quad 3\text{-}2$$

Where: $c_{jkl}$ denotes the element in the reciprocal matrix of sub-criteria $C_{jk}$

$g_{jk}$ denotes the geometric row mean of sub-criterion $C_{jk}$ versus criterion $C_j$

$w_{jk}$ denotes the local weight of sub-criterion $C_{jk}$

p denotes the number of constituents in the set (and also the elements of the corresponding reciprocal matrix)

Unlikely, the local weight of constituents at level 4 (absolute justification) is dependent on the application of the integrative approach. The local weight for selecting new facilities is calculated by the aggregated normalization method, given in Equation 3-3 and 3-4. The local weight for the technology upgrade of the existing facilities is calculated by the base-cased normalization method, given in Equations 3-5 below.

**Aggregated normalization**

In aggregated normalization, judgment values of all alternatives of the subsystem are averaged, and the local weight of the alternatives is measured by how much variation exists from the mean value of the set of alternatives.

$$e_{ijk} = \frac{\sum_{i=1}^{n} a_{ijk}}{n} \qquad 3\text{-}3$$

$$r_{ijk} = a_{ijk} \oslash e_{ijk} \qquad 3\text{-}4$$

Where: $a_{ijk}$ is the absolute judgment of alternative $A_i$ versus sub-criteria $C_{jk}$

$r_{ijk}$ is the local weight of alternative $A_i$ versus sub-criteria $C_{jk}$

n is the number of alternatives in the set

**Base-cased normalization**

In base-cased normalization, one reference alternative (namely base-case alternative) will be appointed and weighting of other alternatives will be specified referring to the base-case alternative.

Base-cased normalization is utilized for the application of technology upgrade of the existing facilities. Thus, the base-case alternative should be the technology currently-in-use in the process. Consequently, this base-cased normalization approach brings the current technology (which is considered as the base-case alternative) into focus of the analysis. The way that other alternatives will be evaluated and weighted on this basis can help facilitate the calculations and obtain more reasonable results.

The local weight of alternative $A_i$ with reference to the base-case alternative $A_o$ is given by:

$$r_{ijk} = a_{ijk} \oslash \sqrt{e_{ijk} \otimes a_{ojk}} \tag{3-5}$$

Where: $a_{ojk}$ is the absolute judgment of the base-case alternative $A_o$ versus sub-criteria $C_{jk}$

3.4.2.3 Aggregate the ratings of alternatives

Weightings of alternatives are step-by-step aggregated along the hierarchy (Equations 3-6 and 3-7). The result of this step is the global weight $r_i$ of alternative $A_i$ with respect to the overall objective O of the DSS.

$$r_{ij} = \frac{1}{p} \otimes \begin{pmatrix} r_{ij1} \otimes w_{j1} \otimes x_{j1} \oplus \dots \\ \oplus\, r_{ijk} \otimes w_{jk} \otimes x_{jk} \oplus \dots \\ \dots \oplus r_{ijp} \otimes w_{jp} \otimes x_{jp} \end{pmatrix} \tag{3-6}$$

$$r_i = \frac{1}{m} \otimes \begin{pmatrix} r_{i1} \otimes w_1 \otimes x_1 \oplus \dots \\ \oplus\, r_{ij} \otimes w_j \otimes x_j \oplus \dots \\ \dots \oplus r_{im} \otimes w_m \otimes x_m \end{pmatrix} \tag{3-7}$$

Where: p, m are the number of constituents in the sub-criteria sets (level 3) and criteria set (level 2) respectively

$x_{jk}$ and $x_j$: factors represent the positive priority and negative priority of the sub-criterion $C_{jk}$ and criterion Cj respectively (Saaty, 2006). x=1 if positive priority, x= -1 if negative priority

3.4.2.4 Defuzzification

After this step, the ratings of the alternatives (value $r_i$) are still in the form of fuzzy numbers, which are not easy to compare and therefore it might not be possible to determine the more preferable one. Therefore, they will be defuzzified and converted to crisp numbers in order to facilitate the ranking process. A number of defuzzification methods have been checked and the centroid point method (Cheng, 1998) was evaluated most appropriate. Ranking of the triangular fuzzy number $i(i_1,i_2,i_3)$ using centroid point method is presented in Equations 3-8 to 3-10.

$$\tilde{x}_i = \frac{1}{3}(i_1 + 2i_2 + i_3) \quad 3\text{-}8$$

$$\tilde{y}_i = \frac{i_1 + 4i_2 + i_3}{3(i_1 + 2i_2 + i_3)} \quad 3\text{-}9$$

$$R_i = \sqrt{(\tilde{x}_i)^2 + (\tilde{y}_i)^2} \quad 3\text{-}10$$

The results of the defuzzification step represent the ratings of the alternatives in ascending order representing the advisability regarding sustainability.

### 3.4.3 Rating and ranking of the whole system

The foregoing calculation process is repeated for each of the three subsystems. As a result, there are three separate ranking lists. The ratings of the whole systems are subsequently determined using Equation 3-11.

$$R_{A_i} = \frac{W_{HS} \otimes R_{HS_i} \oplus W_{PS} \otimes R_{PS_i} \oplus W_{RS} \otimes R_{RS_i}}{3} \quad 3\text{-}11$$

Where: $R_{Ai}$ is the rating of the system alternative $A_i$

$W_{HS}$, $W_{PS}$, $W_{RS}$ are the importance factors of the heating subsystem, processing subsystem and heat recovery subsystem respectively

$R_{HSi}$, $R_{PSi}$, $R_{RSi}$ are respectively the ratings of heating technology $HS_i$, processing technology $PS_i$ and heat recovery technology $RS_i$

The important factors of the subsystems are determined by the comparative justification method, analogously to the determination of the weightings of the criteria and sub-criteria. The processing subsystem is the core component of the thermal process, thus it should be given a higher priority than the heating subsystem and the heat recovery subsystem.

## 3.5 APPLICATION OF THE PROPOSED INTEGRATIVE FRAMEWORK

The proposed integrative framework can be applied to support a decision in either the selection of a new facility or changing the used technology of the existing facility.

### 3.5.1 Decision support for the selection of new facilities

This application is intended to support industrialists in the selection of new facilities. As noted in Section 3.4.2.2, the selection procedure is dominated by the aggregated normalization method and results in a ranked list of thermal process technologies appropriate to the food product under consideration.

In the case of this application, most of the data necessary for the selection process can be retrieved from the database.

### 3.5.2 Decision support for technology change of the existing facilities

This application is intended to support industrialists in the selection of thermal processes for the purpose of upgrading or changing the used technologies in the existing facilities. The technology currently-in-use is taken as the base-case alternative and ratings of other technology alternatives are generally based on this base-case alternative.

Data of the performances of the base-case alternative is requested for the rating and ranking process. For the appraisal of energy performance of the base-case alternative, an energy audit is necessary.

The selection procedure is dominated by the base-cased normalization method and results in the more appropriate technologies in terms of sustainability.

## 3.6 ENERGY PERFORMANCE

In this study, energy performances with respect to energy efficiency, energy recovery and renewable energy consumption are significantly considered in the selection process. Energy performances of the thermal processes are quantitatively estimated by using the thermodynamic models or using the literature data.

### 3.6.1 The process boundary

Under the point of this study, the thermal process system and its subsystems are confined by an imaginary boundary as follows:

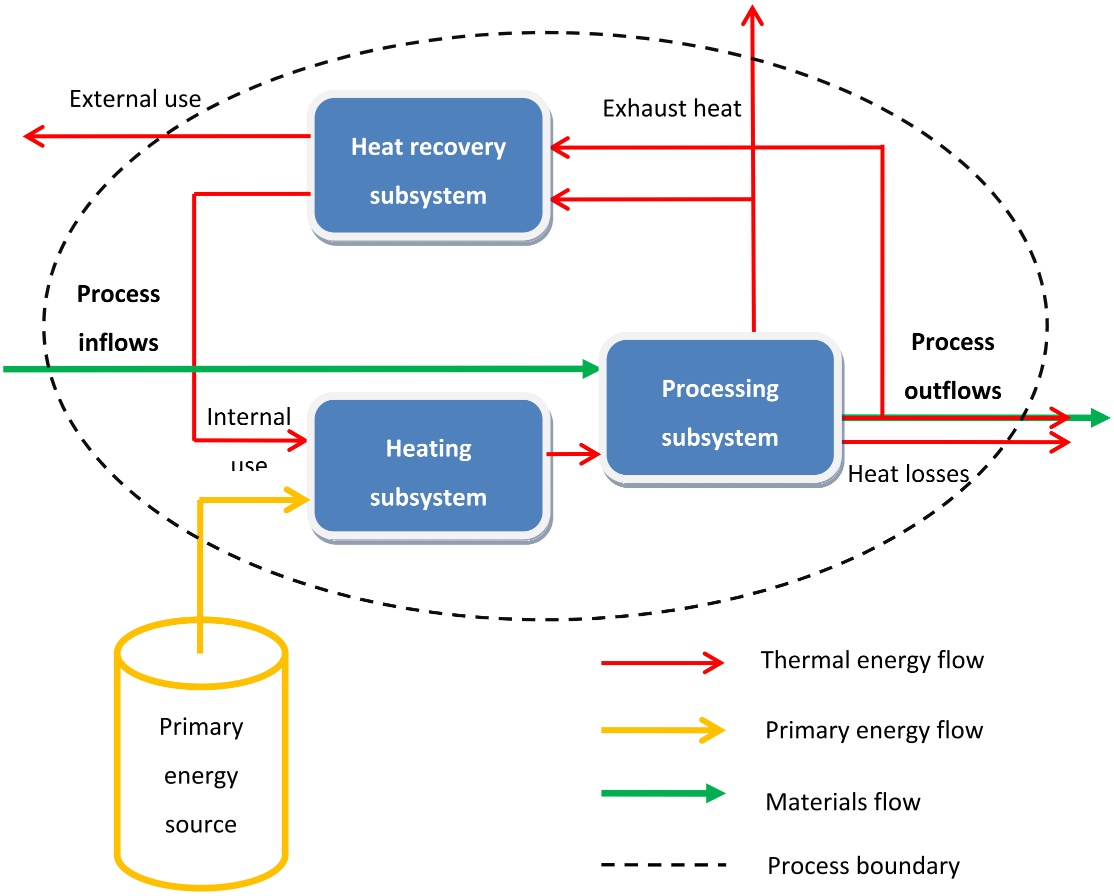


Figure 3-11. Layout of the thermal processes

The heating subsystem converts energy from the primary types (fossil fuel, biomass, solar energy, electricity) to secondary types (steam, hot water, hot oil, hot air). In the processing subsystem, thermal energy is used for raising the product to the process temperature and for thermal treatment of the product. The energy coming out of the process is in the forms of the product outflow, the exhaust heat and the process heat loss. A part or the entire of the energy outflows might be recovered in the heat recovery subsystem.

### 3.6.2 Calculation of the energy performance

The thermal energy flows in the process is demonstrated in the Sankey diagram given in Figure 3-12.

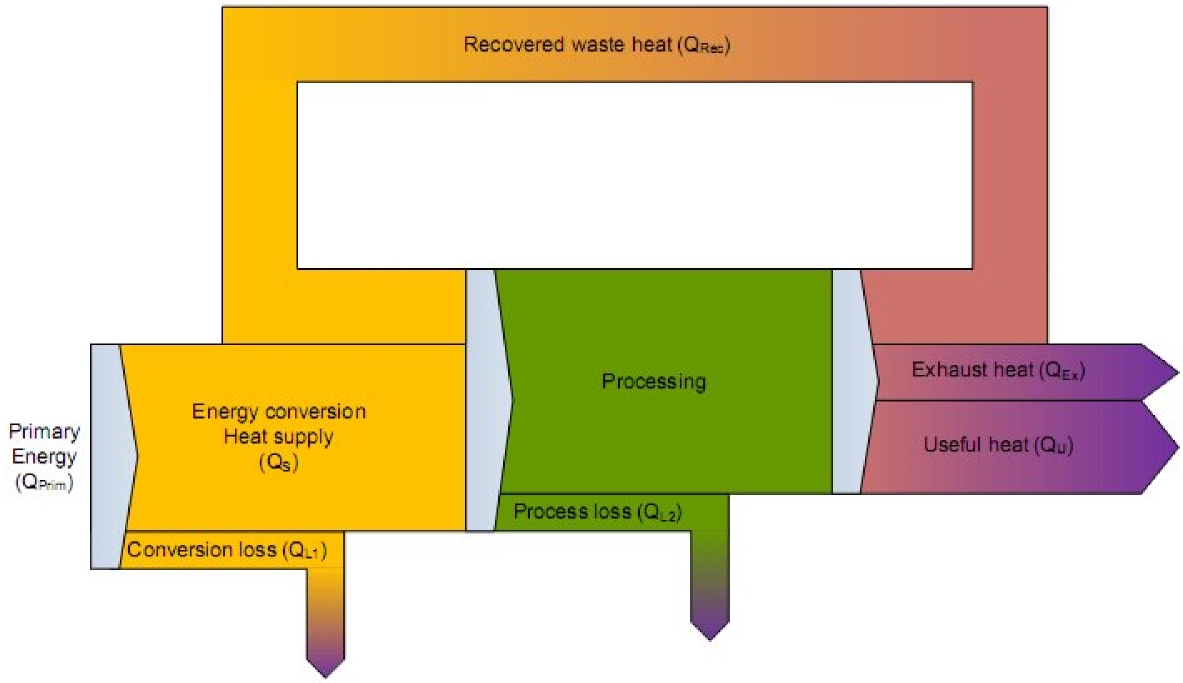


Figure 3-12. A graphical presentation of thermal energy flow in the process

Based on the principle of energy conservation, total heat input ($\Sigma Q_i$) is equal to total heat output ($\Sigma Q_o$) of the process.

$$\sum Q_i = \sum Q_o \qquad 3\text{-}12$$

The total heat input includes the heat supplied by the primary energy source and recovered heat.

$$\sum Q_i = Q_{Prim} + Q_{Rec} \qquad 3\text{-}13$$

The total heat output includes the useful heat, the heat loss and the process waste heat.

$$\sum Q_o = Q_U + Q_{L1} + Q_{L2} + Q_{Ex} + Q_R \qquad 3\text{-}14$$

The thermal efficiency of the process is the measure of the useful heat divided by the total heat input

$$\eta = \frac{Q_U}{\sum Q_i} \qquad 3\text{-}15$$

Considering the utilization of renewable energy, the primary energy use is distinguished between renewable energy and non-renewable energy as in Equation 3-16.

$$Q_{Prim} = Q_{Renew} + Q_{Non-renew} \qquad 3\text{-}16$$

## 3.7 CHAPTER FINDINGS

In this study, an integrative framework has been proposed for the selection of thermal food process technologies considering the sustainability of the process. The selection procedure comprises two main steps: the preliminary and the final selection steps. The preliminary selection step narrows the range of technologies appropriate for the given product and mainly relies on the technical specifications of the thermal processes and the food products. The final selection step provides the ratings and rankings of the technologies based on the appraisal of environmental, economic, and social performances of the process. Energy performance is particularly considered in the selection process due to the fact that thermal process is the most energy-intensive unit operation in food processing sector.

The proposed framework provides decision support for two different applications: selecting new facilities or changing the used technologies of the existing facilities. The rankings of the technologies obtained from these two selection procedures might be different from each other. However, thanks to the reasonable calculation algorithms, only a small variation can be foreseen.

Based on the combination of rule-based techniques and fuzzy analytic hierarchy process, the proposed framework is supposed to be applicable for a wide range of thermal processes of foods, vegetable and fruits including blanching, pasteurization, sterilization, boiling, cooking, drying, etc. The rule-based technique and the fuzzy analytic hierarchy process are not new methods in literature. However, as a combination, they become a new and an efficient approach of decision support for thermal process selection.

The algorithms have been enhanced to overcome the challenge of defining the ratings and rankings for a large number of alternatives. This allows for the selection of the processes that have a wide range of technologies, for example the drying process, or the pasteurization process.

The configuration of a thermal process from three separate subsystems ensures to cover a wide range of technology alternatives available on the market. This also helps facilitate the evaluation of energy performance of the process.

Using the factor of reverse attribute values, the problem of positive and negative attributes has been properly settled in the calculation algorithms.

Dealing with the insufficiency and uncertainty faced in most decision making problems, the data for the rating and ranking process is generally specified in triangular fuzzy number. Calculating fuzzy numbers might be troublesome and tedious, however the reliability of the obtained results can be enhanced.

# 4. THE DECISION SUPPORT SYSTEM FOR THE SELECTION OF FOOD DRYING TECHNOLOGIES

The proposed integrative framework is hereupon realized in the development of a decision support system (DSS) for the selection of food drying technologies. This DSS is programmed on MS-Excel and the illustrative figures given in this section are entirely taken from this Excel-based DSS.

## 4.1 SUBDIVISION OF THE DRYING SYSTEM

Following the 3-subsystem approach as described in Section 3.2, the classification indicators of the subsystems of drying processes are proposed as in Figure 4-2.

Correspondingly, for each subsystem a number of technologies available on the market are explicitly identified. A total of 6 heating technologies, 16 processing technologies and 3 heat recovery technologies have been collected so far as shown in the following figure.

| Processing subsystem | | Heating subsystem | | Heat recovery subsystem | |
|---|---|---|---|---|---|
| **ID** | **Technology** | **ID** | **Technology** | **ID** | **Technology** |
| PS01 | Contact cabinet dryer | HS01 | Boiler/heater-non renewable energy | RS01 | No heat recovery |
| PS02 | Contact tunnel dryer | HS02 | Boiler-renewable energy | RS02 | Exhaust air recirculation |
| PS03 | Plate dryer | HS03 | Boiler-mixed type | RS03 | Exhaust air heat exchanger |
| PS04 | Contact conveyor dryers | HS04 | Solar collector | | |
| PS05 | Rotary steam tube dryer | HS05 | Heat pump | | |
| PS06 | Drum dryer | HS06 | Refrigeration plant | | |
| PS07 | Direct cabinet dryer | | | | |
| PS08 | Direct tunnel dryer | | | | |
| PS09 | Direct conveyor dryers | | | | |
| PS10 | Chamber/bin dryer | | | | |
| PS11 | Direct rotary dryer | | | | |
| PS12 | Fluidized bed dryer | | | | |
| PS13 | Spouted bed dryer | | | | |
| PS14 | Spray dryer | | | | |
| PS15 | Pneumatic flash dryer | | | | |
| PS16 | Freeze dryer | | | | |

Figure 4-1. Technologies of the dryer subsystem

| Subsystem | | Classification criteria | | | |
|---|---|---|---|---|---|
| HS | Heating subsystem | H1 | Drying medium | H11 | Hot air/gas |
| | | | | H12 | No drying medium |
| | | | | H13 | Solar radiation |
| | | H2 | Type of primary energy used | H21 | Fossil fuel |
| | | | | H22 | Biomass |
| | | | | H23 | Electric |
| | | | | H24 | Solar energy |
| | | | | H25 | Mixed type of biomass and fossil fuel or electric |
| | | | | H26 | Mixed type of solar and fossil fule or electric |
| PS | Processing subsystem | P1 | Operation mode | P11 | Batch |
| | | | | P12 | Continuous |
| | | P2 | Heating mode | P21 | Direct |
| | | | | P22 | Indirect |
| | | P3 | Drying medium | P31 | Hot air/gas |
| | | | | P32 | No drying medium |
| | | | | P33 | Solar radiation |
| | | P4 | Heat input type | P41 | Convection |
| | | | | P42 | Conduction |
| | | | | P43 | Radiation |
| | | | | P44 | Electromagnetic fields |
| | | | | P45 | Combination of heat transfer modes |
| | | | | P46 | Intermittent or continuous |
| | | | | P47 | Adiabatic or non-adiabatic |
| | | P5 | Drying temperature | P51 | Below boiling temperature |
| | | | | P52 | Above boiling temperature |
| | | | | P53 | Below freezing point |
| | | P6 | Relative motion between drying medium and drying solid | P61 | No relative motion (case of stationary material) |
| | | | | P62 | Co-current |
| | | | | P63 | Counter-current |
| | | | | P64 | Mixed flow |
| | | | | P65 | Cross-flow |
| | | P7 | Residence time within dryer | P71 | 0-10 seconds |
| | | | | P72 | 10-30 seconds |
| | | | | P73 | 5-10 minutes |
| | | | | P74 | 10-60 minutes |
| | | | | P75 | 1-6 hours |
| | | | | P76 | More than 6 hours |
| | | P8 | Operating pressure | P81 | Low pressure (vacuum) |
| | | | | P82 | Near atmospheric |
| | | | | P83 | high pressure (5 bar) |
| RS | Heat recovery subsystem | R1 | Heat recovery | R11 | Venting (no recovery) |
| | | | | R12 | Exhaust air recirculation |
| | | | | R13 | Exhaust air heat exchanger |

Figure 4-2. Classification indicators of the dryer subsystems

The whole system technologies are configured by the appropriate combinations of the subsystem technologies. In so doing, there have been 109 combinations corresponding to 109 drying technology alternatives that can be found in practice. Figure 4-3 shows several drying technologies configured in this way, the whole list is presented in Annex 1-1.

| No. | Technology ID | Drying technology alternative | Processing subsystem | Heating subsystem | Heat recovery subsystem |
|---|---|---|---|---|---|
| 1 | A001 | Contact cabinet dryer - Boiler/heater-non renewable energy - No heat recover | PS01 | HS01 | RS01 |
| 2 | A004 | Contact cabinet dryer - Boiler-renewable energy - No heat recovery | PS01 | HS02 | RS01 |
| 3 | A007 | Contact cabinet dryer - Boiler-mixed type - No heat recovery | PS01 | HS03 | RS01 |
| 4 | A019 | Contact tunnel dryer - Boiler/heater-non renewable energy - No heat recovery | PS02 | HS01 | RS01 |
| 5 | A022 | Contact tunnel dryer - Boiler-renewable energy - No heat recovery | PS02 | HS02 | RS01 |
| 6 | A025 | Contact tunnel dryer - Boiler-mixed type - No heat recovery | PS02 | HS03 | RS01 |
| 7 | A037 | Plate dryer - Boiler/heater-non renewable energy - No heat recovery | PS03 | HS01 | RS01 |
| 8 | A040 | Plate dryer - Boiler-renewable energy - No heat recovery | PS03 | HS02 | RS01 |
| 9 | A043 | Plate dryer - Boiler-mixed type - No heat recovery | PS03 | HS03 | RS01 |
| 10 | A055 | Contact conveyor dryers - Boiler/heater-non renewable energy - No heat reco | PS04 | HS01 | RS01 |
| 11 | A058 | Contact conveyor dryers - Boiler-renewable energy - No heat recovery | PS04 | HS02 | RS01 |
| 12 | A061 | Contact conveyor dryers - Boiler-mixed type - No heat recovery | PS04 | HS03 | RS01 |
| 13 | A073 | Rotary steam tube dryer - Boiler/heater-non renewable energy - No heat reco | PS05 | HS01 | RS01 |

Figure 4-3. An extract of the list of drying technologies

## 4.2 SELECTION OF FOOD DRYING TECHNOLOGIES

The selection procedure consists of 2 main steps: preliminary selection which narrows the range of dryers suitable for the product under consideration and the final selection which provides ratings and rankings of dryers within the predefined range according to a set of appropriate criteria. Table 4-1 provides an overview of the proposed DSS.

Table 4-1. Overview of the DSS for the selection of food drying technologies

| *Selection step* | *Method* | *Input information* | *Result* |
|---|---|---|---|
| Preliminary selection | Rule-based method | Material and dried product characteristics:<br>Physical form of feed<br>Nature of wet feed<br>Special requirements of product<br>Allowable drying temperature<br>Product throughput<br>Mode of upstream and downstream operations | List of drying technologies appropriate for the given food product |

| ***Selection step*** | ***Method*** | ***Input information*** | ***Result*** |
|---|---|---|---|
| Final selection | Fuzzy AHP method | Performance of the drying system:<br>Environmental performance: specific heat demand, thermal efficiency, heat recovery ratio, renewable energy usage<br>Economic performance: investment cost, operation cost<br>Social performance: final product quality, fire hazard and explosion hazard, convenience of installation and operation | Rankings of drying technologies for the final decision |

The core components of this DSS are the database of drying technologies and the database of dryers' performance with respect to the energy, economic and social criteria. To facilitate the programming, the databases are computed in two ways: Boolean data type in the preliminary selection step and triangular fuzzy number data type in the final selection step. A huge amount of data has been carefully screened and collected in order to make the databases as exhaustive and consistent as possible.

### 4.2.1 Preliminary selection step

The preliminary selection of food drying technologies is not a step-by-step process. Relied on the rule-based method, it constitutes two interactive components: the database and the rule-base. The Boolean data type is used to signify the technical specifications of the drying subsystem technologies and the food products as well as the configuration of the overall drying systems from the combinations of the modular subsystem technologies. It is also used to signify the capabilities of the technologies and the product specifications. The programming of Boolean in the DSS is that the TRUE or FALSE value is used to indicate the proposition of the aforementioned specifications, combinations, and capabilities.

#### 4.2.1.1 The system database

**Drying technology database**

As presented in part 4.1 of this report, the drying system is configured from the combination of 3 subsystems including heating subsystem, processing subsystem and heat recovery subsystem. Accordingly, three separate groups of data concerning the aforementioned subsystems have been profiled in the database. In MS-Excel, the specifications of the subsystems are expressed as logical statements, using "X" and "-" characters to represent the Boolean values with respect to the classification indicators. Figure 4-4 shows an example of the specification of the heating subsystem technologies. The other subsystems can be found in Annex 2-1 to Annex 2-3.

| ID | Technology | H1 | | | H2 | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|
| | | H11 | H12 | H13 | H21 | H22 | H23 | H24 | H25 | H26 |
| HS01 | Boiler/heater-non renewable | X | X | - | X | - | - | - | - | - |
| HS02 | Boiler-renewable energy | X | X | - | - | X | - | - | - | - |
| HS03 | Boiler-mixed type | X | X | - | - | - | X | X | - | - |
| HS04 | Solar collector | - | - | X | - | - | - | - | - | X |
| HS05 | Heat pump | X | - | - | - | - | - | - | X | - |
| HS06 | Refrigeration plant | - | X | - | - | - | - | - | X | - |

Figure 4-4. Specification of the processing subsystem

The whole drying system is then configured by properly assembling these subsystems (see Figure 4-5 below). Similarly, Boolean values are used to present the possible combinations of the subsystems.

| DRYING TECHNOLOGY | | PROCESSING SUBSYSTEM | | | | | | | | | | | | | | | | HEATING SUBSYSTEM | | | | | | HEAT RECOVERY | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| Alternative | ID | PS01 | PS02 | PS03 | PS04 | PS05 | PS06 | PS07 | PS08 | PS09 | PS10 | PS11 | PS12 | PS13 | PS14 | PS15 | PS16 | HS01 | HS02 | HS03 | HS04 | HS05 | HS06 | RS01 | RS02 | RS03 |
| Contact cabinet dryer - Boiler/heater-non renewable energy | A001 | X | - | - | - | - | - | - | - | - | - | - | - | - | - | - | - | X | - | - | - | - | - | X | - | - |
| Contact cabinet dryer - Boiler/heater-non renewable energy | A002 | X | - | - | - | - | - | - | - | - | - | - | - | - | - | - | - | X | - | - | - | - | - | - | X | - |
| Contact cabinet dryer - Boiler/heater-non renewable energy | A003 | X | - | - | - | - | - | - | - | - | - | - | - | - | - | - | - | X | - | - | - | - | - | - | - | X |
| Contact cabinet dryer - Boiler-renewable energy - No heat re | A004 | X | - | - | - | - | - | - | - | - | - | - | - | - | - | - | - | - | X | - | - | - | - | X | - | - |
| Contact cabinet dryer - Boiler-renewable energy - Exhaust a | A005 | X | - | - | - | - | - | - | - | - | - | - | - | - | - | - | - | - | X | - | - | - | - | - | X | - |
| Contact cabinet dryer - Boiler-renewable energy - Exhaust a | A006 | X | - | - | - | - | - | - | - | - | - | - | - | - | - | - | - | - | X | - | - | - | - | - | - | X |
| Contact cabinet dryer - Boiler-mixed type - No heat recovery | A007 | X | - | - | - | - | - | - | - | - | - | - | - | - | - | - | - | - | - | X | - | - | - | X | - | - |
| Contact cabinet dryer - Boiler-mixed type - Exhaust air recir | A008 | X | - | - | - | - | - | - | - | - | - | - | - | - | - | - | - | - | - | X | - | - | - | - | X | - |
| Contact cabinet dryer - Boiler-mixed type - Exhaust air heat | A009 | X | - | - | - | - | - | - | - | - | - | - | - | - | - | - | - | - | - | X | - | - | - | - | - | X |
| Contact tunnel dryer - Boiler/heater-non renewable energy - | A019 | - | X | - | - | - | - | - | - | - | - | - | - | - | - | - | - | X | - | - | - | - | - | X | - | - |
| Contact tunnel dryer - Boiler/heater-non renewable energy - | A020 | - | X | - | - | - | - | - | - | - | - | - | - | - | - | - | - | X | - | - | - | - | - | - | X | - |
| Contact tunnel dryer - Boiler/heater-non renewable energy - | A021 | - | X | - | - | - | - | - | - | - | - | - | - | - | - | - | - | X | - | - | - | - | - | - | - | X |
| Contact tunnel dryer - Boiler-renewable energy - No heat rec | A022 | - | X | - | - | - | - | - | - | - | - | - | - | - | - | - | - | - | X | - | - | - | - | X | - | - |
| Contact tunnel dryer - Boiler-renewable energy - Exhaust air | A023 | - | X | - | - | - | - | - | - | - | - | - | - | - | - | - | - | - | X | - | - | - | - | - | X | - |
| Contact tunnel dryer - Boiler-renewable energy - Exhaust air | A024 | - | X | - | - | - | - | - | - | - | - | - | - | - | - | - | - | - | X | - | - | - | - | - | - | X |
| Contact tunnel dryer - Boiler-mixed type - No heat recovery | A025 | - | X | - | - | - | - | - | - | - | - | - | - | - | - | - | - | - | - | X | - | - | - | X | - | - |
| Contact tunnel dryer - Boiler-mixed type - Exhaust air recircu | A026 | - | X | - | - | - | - | - | - | - | - | - | - | - | - | - | - | - | - | X | - | - | - | - | X | - |
| Contact tunnel dryer - Boiler-mixed type - Exhaust air heat e | A027 | - | X | - | - | - | - | - | - | - | - | - | - | - | - | - | - | - | - | X | - | - | - | - | - | X |
| Plate dryer - Boiler/heater-non renewable energy - No heat r | A037 | - | - | X | - | - | - | - | - | - | - | - | - | - | - | - | - | X | - | - | - | - | - | X | - | - |
| Plate dryer - Boiler/heater-non renewable energy - Exhaust a | A038 | - | - | X | - | - | - | - | - | - | - | - | - | - | - | - | - | X | - | - | - | - | - | - | X | - |
| Plate dryer - Boiler/heater-non renewable energy - Exhaust a | A039 | - | - | X | - | - | - | - | - | - | - | - | - | - | - | - | - | X | - | - | - | - | - | - | - | X |
| Plate dryer - Boiler-renewable energy - No heat recovery | A040 | - | - | X | - | - | - | - | - | - | - | - | - | - | - | - | - | - | X | - | - | - | - | X | - | - |
| Plate dryer - Boiler-renewable energy - Exhaust air recircula | A041 | - | - | X | - | - | - | - | - | - | - | - | - | - | - | - | - | - | X | - | - | - | - | - | X | - |
| Plate dryer - Boiler-renewable energy - Exhaust air heat excl | A042 | - | - | X | - | - | - | - | - | - | - | - | - | - | - | - | - | - | X | - | - | - | - | - | - | X |
| Plate dryer - Boiler-mixed type - No heat recovery | A043 | - | - | X | - | - | - | - | - | - | - | - | - | - | - | - | - | - | - | X | - | - | - | X | - | - |
| Plate dryer - Boiler-mixed type - Exhaust air recirculation | A044 | - | - | X | - | - | - | - | - | - | - | - | - | - | - | - | - | - | - | X | - | - | - | - | X | - |
| Plate dryer - Boiler-mixed type - Exhaust air heat exchanger | A045 | - | - | X | - | - | - | - | - | - | - | - | - | - | - | - | - | - | - | X | - | - | - | - | - | X |
| Contact conveyor dryers - Boiler/heater-non renewable ener | A055 | - | - | - | X | - | - | - | - | - | - | - | - | - | - | - | - | X | - | - | - | - | - | X | - | - |
| Contact conveyor dryers - Boiler/heater-non renewable ener | A056 | - | - | - | X | - | - | - | - | - | - | - | - | - | - | - | - | X | - | - | - | - | - | - | X | - |

Figure 4-5. Configuration of drying technologies from the combination of the subsystem technologies

**Product database**

The categorization of food products is defined in accordance with the NACE code's classification; subsector DA15.3 - Production of food and vegetable products. For the preliminary selection purpose, the technical specifications of the substances to be processed concern the physical form of feed, nature of wet feed, special requirements of product, and allowable drying temperature (as shown in Figure 4-6).

| | | | |
|---|---|---|---|
| PP | Physical form of feed | PP1 | Fine powder/granular |
| | | PP2 | Coarse powder, grains and small pieces |
| | | PP3 | Large pieces, flakes and extrudates |
| | | PP4 | Paste/ slurry |
| | | PP5 | Liquid solultion |
| | | PP6 | Continuous sheets |
| PW | Nature of wet feed | PW1 | Free flowing, non-cohesive, loose |
| | | PW2 | Cohesive |
| | | PW3 | Lumpy |
| | | PW4 | Viscous |
| PR | Special requirements of product | PR1 | Fragile |
| | | PR2 | Heat-sensitive |
| | | PR3 | Uncontaminated |
| | | PR4 | Very low final moisture |
| | | PR5 | High value |
| | | PR6 | Nonaqueous solution reclamation |
| PA | Allowable drying temperature | PA1 | Bellow boiling temperature |
| | | PA2 | Above boiling temperature |
| | | PA3 | Below freezing temperature |

Figure 4-6. Specification indicators of foods

The specifications are then expressed as Boolean data type in the same manner as the drying technology database.

| Code | Product | Product specification | | | | | | | | | | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | | Physical form of feed | | | | | | Nature of wet feed | | | | Special requirements of product | | | | | | Allowable drying temperature | | |
| | | PP1 | PP2 | PP3 | PP4 | PP5 | PP6 | PW1 | PW2 | PW3 | PW4 | PR1 | PR2 | PR3 | PR4 | PR5 | PR6 | PA1 | PA2 | PA3 |
| DA15.3 | PRODUCTION OF FOOD AND VEGETABLE PRODUCTS | | | | | | | | | | | | | | | | | | | |
| DA15.33 | Production and preserving of fruit and vegetable | | | | | | | | | | | | | | | | | | | |
| DA15.331 | Whole or cut fruit and vegetable | | | | | | | | | | | | | | | | | | | |
| DA15.331.1 | Banana | - | - | X | - | - | - | X | - | - | - | - | - | X | - | - | - | X | - | X |
| DA15.331.2 | Grapes | - | - | X | - | - | - | X | - | - | - | - | - | X | - | - | - | X | X | X |
| DA15.331.3 | Longan, lychee | - | - | X | - | - | - | X | - | - | - | - | - | X | - | - | - | X | X | X |
| DA15.331.4 | Japanese plum | - | - | X | - | - | - | X | - | - | - | - | - | X | - | - | - | X | X | X |
| DA15.331.5 | Apricot | - | - | X | - | - | - | X | - | - | - | - | - | X | - | - | - | X | X | X |
| DA15.331.6 | Mushroom (straw mushroom) | - | - | X | - | - | - | X | - | - | - | - | - | X | - | - | - | X | X | X |
| DA15.331.7 | Tomato | - | - | X | - | - | - | X | - | - | - | - | - | X | - | - | - | X | X | X |
| DA15.331.8 | Copra | - | - | X | - | - | - | X | - | - | - | - | X | X | - | - | - | X | X | X |
| DA15.331.9 | Onion | - | - | X | - | - | - | X | - | - | - | - | - | X | - | - | - | X | X | X |
| DA15.331.11 | Pinapple | - | - | X | - | - | - | X | - | - | - | - | - | X | - | - | - | X | X | X |
| DA15.331.12 | Mango | - | - | X | - | - | - | X | - | - | - | - | - | X | - | - | - | X | X | X |
| DA15.333 | Root vegetable | | | | | | | | | | | | | | | | | | | |
| DA15.333.1 | Sweet potato | - | - | X | - | - | - | X | - | - | - | - | - | X | - | - | - | X | X | X |
| DA15.333.2 | Beets | - | - | X | - | - | - | X | - | - | - | - | - | X | - | - | - | X | X | X |
| DA15.333.3 | Cassava | - | - | X | - | - | - | X | - | - | - | - | - | X | - | - | - | X | X | X |
| DA15.333.4 | Potato | - | - | X | - | - | - | X | - | - | - | - | - | X | - | - | - | X | X | X |
| DA15.331.10 | Carrot | - | - | X | - | - | - | X | - | - | - | - | - | X | - | - | - | X | X | X |

Figure 4-7. An extract of the product database

**Capability database**

The expertise on the capability of the subsystems' technologies with respect to the attributes of the product specification is recorded in Boolean that allows for the implementation of the production rules. Two user-defined specifications related to the mode of operation and product throughput are also included in the capability database. An example of the knowledge domain on the capability of the processing subsystem is presented in Figure 4-8.

#### 4.2.1.2 The rule-base

Based on the IF-THEN rule format, the preliminary selection is processed as follows:

IF <The capability of the subsystem technology and the given physical form of feed specification is "X">

AND <The capability of the subsystem technology and the given nature of wet feed specification is "X">

AND <The capability of the subsystem technology and the given specific requirements of product specification is "X">

AND <The capability of the subsystem technology and the given allowable drying temperature specification is "X">

AND <The capability of the subsystem technology and the given mode of upstream and downstream operation specification is "X">

AND <The capability of the subsystem technology and the given product throughput specification is "X">

THEN <select the subsystem technology>

The rules scan all the subsystem technology alternatives available in the technology database and result in the alternatives that are capable of all the specifications of the given product. There will be three lists of pre-selected technology alternatives corresponding to the three subsystems of the process and the other list of the overall system technology alternatives that are configured from the appropriate combinations of the subsystems' technologies.

| HEATING SUBSYSTEM | | Physical form of feed | | | | | | Nature of wet feed | | | | Special requirements of product | | | | | | Allowable drying temperature | | | Product throughput | | | Mode of upstream and | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| ID | Technology | PP1 | PP2 | PP3 | PP4 | PP5 | PP6 | PW1 | PW2 | PW3 | PW4 | PR1 | PR2 | PR3 | PR4 | PR5 | PR6 | PA1 | PA2 | PA3 | PT1 | PT2 | PT3 | PM1 | PM2 |
| HS01 | Boiler/heater-non renewable energy | X | X | X | X | X | X | X | X | X | X | X | X | X | - | - | - | X | X | - | X | X | X | X | X |
| HS02 | Boiler-renewable energy | X | X | X | X | X | X | X | X | X | X | X | X | X | - | - | - | X | X | - | X | X | X | X | X |
| HS03 | Boiler-mixed type | X | X | X | X | X | X | X | X | X | X | X | X | X | - | - | - | X | X | - | X | X | X | X | X |
| HS04 | Solar collector | X | X | X | X | X | X | X | X | X | X | X | - | X | - | - | - | X | - | - | X | X | X | X | X |
| HS05 | Heat pump | X | X | X | X | X | X | X | X | X | X | X | X | X | X | X | X | X | - | - | X | X | X | X | X |
| HS06 | Refrigeration plant | X | X | X | X | X | X | X | X | X | X | X | X | X | X | X | X | - | - | X | X | - | - | X | - |

| PROCESSING SUBSYSTEM | | Physical form of feed | | | | | | Nature of wet feed | | | | Special requirements of product | | | | | | Allowable drying temperature | | | Product throughput | | | Mode of upstream | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| ID | Technology | PP1 | PP2 | PP3 | PP4 | PP5 | PP6 | PW1 | PW2 | PW3 | PW4 | PR1 | PR2 | PR3 | PR4 | PR5 | PR6 | PA1 | PA2 | PA3 | PT1 | PT2 | PT3 | PM1 | PM2 |
| PS01 | Contact cabinet dryer | X | X | X | - | X | - | X | X | - | - | X | X | X | X | X | - | X | X | | X | - | - | X | - |
| PS02 | Contact tunnel dryer | X | X | X | - | - | - | X | | - | - | | | X | X | X | - | X | X | - | - | X | - | X | X |
| PS03 | Plate dryer | X | X | - | - | - | - | X | - | - | - | - | - | X | X | X | - | X | X | - | X | X | - | - | X |
| PS04 | Contact conveyor dryers | - | X | X | - | - | - | X | X | - | - | X | X | X | X | X | - | X | X | - | - | X | - | - | X |
| PS05 | Rotary steam tube dryer | X | X | X | - | - | - | X | X | - | - | | X | X | X | - | - | X | X | - | X | X | - | - | X |
| PS06 | Drum dryer | - | - | - | X | X | - | - | - | - | - | - | X | X | X | - | X | X | X | - | - | X | X | - | X |
| PS07 | Direct cabinet dryer | X | X | X | - | X | - | X | X | - | - | X | X | X | X | - | - | X | X | - | X | - | - | X | - |
| PS08 | Direct tunnel dryer | X | X | X | - | - | - | X | | - | - | | | X | X | - | - | X | X | - | - | X | - | X | X |
| PS09 | Direct conveyor dryers | - | X | X | - | - | - | X | X | - | - | X | X | X | X | - | - | X | X | - | - | X | - | - | X |
| PS10 | Chamber/bin dryer | - | X | - | - | - | - | X | - | - | - | - | - | X | - | - | - | X | - | - | - | X | X | X | - |
| PS11 | Direct rotary dryer | X | X | X | - | - | - | X | X | - | - | | X | X | X | - | - | X | X | - | X | X | - | - | X |
| PS12 | Fluidized bed dryer | X | X | X | - | - | - | X | - | - | - | X | - | X | - | - | - | X | X | - | X | X | - | X | X |
| PS13 | Spouted bed dryer | - | X | - | X | - | - | - | - | - | - | - | - | X | - | - | - | X | - | - | - | X | X | - | X |
| PS14 | Spray dryer | - | - | - | X | X | - | - | - | - | - | - | X | X | - | - | - | - | X | - | - | X | X | - | X |
| PS15 | Pneumatic flash dryer | X | X | - | X | - | - | X | X | - | - | - | - | X | - | - | - | X | X | - | - | X | X | - | X |
| PS16 | Freeze dryer | X | X | X | - | X | - | X | X | - | - | X | X | X | X | X | - | - | - | X | X | - | - | X | - |

| HEAT RECOVERY SUBSYSTEM | | Physical form of feed | | | | | Nature of wet feed | | | | Special requirements of product | | | | | | Allowable drying temperature | | | Product throughput | | | Mode of upstream and | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| ID | Technology | PP1 | PP3 | PP4 | PP5 | PP6 | PW1 | PW2 | PW3 | PW4 | PR1 | PR2 | PR3 | PR4 | PR5 | PR6 | PA1 | PA2 | PA3 | PT1 | PT2 | PT3 | PM1 | PM2 |
| RS01 | No heat recovery | X | X | X | X | X | X | X | X | X | X | X | X | X | X | X | X | X | X | X | X | X | X | X |
| RS02 | Exhaust air recirculation | X | X | X | X | X | X | X | X | X | X | X | X | X | X | X | X | X | X | X | X | X | X | X |
| RS03 | Exhaust air heat exchanger | X | X | X | X | X | X | X | X | X | X | X | X | X | X | X | X | X | X | X | X | X | X | X |

Figure 4-8. Knowledge domain of the capability of dryer subsystems' technologies and food product specifications

### 4.2.2 Final selection step

In the final selection step, the subsystem technologies pre-selected in the first step are rated and ranked using fuzzy AHP technique.

#### 4.2.2.1 The hierarchical criteria system

The 4-level hierarchical criteria system for food dryer selection is displayed in Figure 4-9.

| | | | | | | | |
|---|---|---|---|---|---|---|---|
| O | Sustainable food drying system | C1 | Environmental performance | C11 | Specific heat requirement | PS01 | Contact cabinet dryer |
| | | | | C12 | Thermal energy efficiency | PS02 | Contact tunnel dryer |
| | | | | C13 | Heat recovery ratio | PS04 | Contact conveyor dryers |
| | | | | C14 | Renewable energy utilization | PS05 | Rotary steam tube dryer |
| | | C2 | Economic performance | C21 | Investment cost | PS07 | Direct cabinet dryer |
| | | | | C22 | Operation cost | PS08 | Direct tunnel dryer |
| | | C3 | Social performance | C31 | Final product quality | PS09 | Direct conveyor dryers |
| | | | | C32 | Fire hazard and explosion hazard | PS11 | Direct rotary dryer |
| | | | | C33 | Convience of installation and operati | … | … |
| **Level 1: Objective** | | **Level 2: criteria** | | **Level 3: sub-criteria** | | **Level 4: Subsystem alternatives** | |

Figure 4-9. The hierarchical criteria system for food dryer selection

#### 4.2.2.2 Justification of constituents in the hierarchical criteria system

**Absolute judgment**

Absolute judgment is applied for the justification of alternatives (level 4) with respect to the sub-criteria (level 3). This also means the justification of drying technologies with respect to the sub-criteria of environmental, economic and social performances.

Sustainability in term of energy use is especially highlighted in this study, therefore energy performance is considered more important than the other criteria. Criteria of product quality and economic performance are considered as similar references. More details on the evaluation criteria can be seen in Section 4.3 of this report.

Justification of alternatives regarding energy performance criteria are calculated with fuzzy number arithmetic using the formulas described in Section 4.4. Justification of alternatives with respect to criteria of economic performance and social performance are presented in the form of linguistic assessments, and then transformed to TFNs by a proper conversion scale as presented in the Section 3.4.2.1. Reviews and evaluations of economic performance and social performance of various drying technologies are displayed in Section 4.3 of this report.

**Comparative judgment**

Comparative judgment is applied for the justification of constituents of the level 2 (criteria) and level 3 (sub-criteria) in the hierarchy. A reciprocal matrix will be set up for each set of constituents to specify the reference of the constituents of that set with respect to the constituent of the upper level (as outlined in Section 3.4.2.1).

Figure 4-10 below displays the justification as linguistic assessments and TFNs of the constituents at levels 2 and level 3 of the hierarchy. The cells in the sub-table "Triangular fuzzy number scale" represent the elements of the reciprocal matrix of the constituent (values $c_{jkl}$ in the final selection process).

| CRITERIA | | LINGUISTIC SCALE | | | TRIANGULAR FUZZY NUMBER SCALE | | |
|---|---|---|---|---|---|---|---|
| **Code** | **Name** | **C1** | **C2** | **C3** | **C1** | **C2** | **C3** |
| C1 | Environmental performance | EQ | H | H | (1 , 1 , 1) | (1 , 3 , 5) | (1 , 3 , 5) |
| C2 | Economic performance | | EQ | M | (1 , 3 , 5) | (1 , 1 , 1) | (0.33 , 1 , 3) |
| C3 | Social performance | | | EQ | (1 , 3 , 5) | (0.33 , 1 , 3) | (1 , 1 , 1) |

**Environmental performance**

| SUB-CRITERIA | | LINGUISTIC SCALE | | | | TRIANGULAR FUZZY NUMBER SCALE | | | |
|---|---|---|---|---|---|---|---|---|---|
| **Code** | **Name** | **C11** | **C12** | **C13** | **C14** | **C11** | **C12** | **C13** | **C14** |
| C11 | Specific heat requirement | EQ | M | M | M | (1 , 1 , 1) | (0.33 , 1 , 3) | (0.33 , 1 , 3) | (0.33 , 1 , 3) |
| C12 | Thermal energy efficiency | | EQ | M | M | (0.33 , 1 , 3) | (1 , 1 , 1) | (0.33 , 1 , 3) | (0.33 , 1 , 3) |
| C13 | Heat recovery ratio | | | EQ | M | (0.33 , 1 , 3) | (0.33 , 1 , 3) | (1 , 1 , 1) | (0.33 , 1 , 3) |
| C14 | Renewable energy utilization | | | | EQ | (0.33 , 1 , 3) | (0.33 , 1 , 3) | (0.33 , 1 , 3) | (1 , 1 , 1) |

**Economic performance**

| SUB-CRITERIA | | LINGUISTIC | | TRIANGULAR FUZZY NUMBER | |
|---|---|---|---|---|---|
| **Code** | **Name** | **C21** | **C22** | **C21** | **C22** |
| C21 | Investment cost | EQ | M | (1 , 1 , 1) | (0.33 , 1 , 3) |
| C22 | Operation cost | | EQ | (0.33 , 1 , 3) | (1 , 1 , 1) |

**Social performance**

| CRITERIA | | LINGUISTIC SCALE | | | TRIANGULAR FUZZY NUMBER SCALE | | |
|---|---|---|---|---|---|---|---|
| **Code** | **Name** | **C31** | **C32** | **C33** | **C31** | **C32** | **C33** |
| C31 | Final product quality | EQ | H | H | (1 , 1 , 1) | (1 , 3 , 5) | (1 , 3 , 5) |
| C32 | Fire hazard and explosion hazard | | EQ | M | (1 , 3 , 5) | (1 , 1 , 1) | (0.33 , 1 , 3) |
| C33 | Convience of installation and operation | | | EQ | (1 , 3 , 5) | (0.33 , 1 , 3) | (1 , 1 , 1) |

Figure 4-10. Justification of the sub-criteria and criteria

### 4.2.2.3 Normalization of judgment data

Normalization transforms the justification of constituents to relative weighting values. There are 2 methods of normalization: aggregated normalization and base-cased normalization. The aggregated normalization is applied for the selection of new facilities (application 1) while the base-cased normalization is applied for that of technology change of the existing facilities (application 2).

Using Equations 3-1 and 3-2, the local weights of constituents in the hierarchy are successionally computed (values $r_{ijk}$). Figure 4-11a Figure 4-11b respectively present the local weights of alternatives in the application 1 and application 2.

a) Aggregated normalization

| PROCESSING SUBSYSTEM | | SUB-CRITERIA | | | | | | |
|---|---|---|---|---|---|---|---|---|
| ID | Technology | $C_{11}$ | $C_{12}$ | $C_{21}$ | $C_{22}$ | $C_{31}$ | $C_{32}$ | $C_{33}$ |
| PS01 | Contact cabinet dryer | (-4.44 , -0.56 , -0.1) | (0.3 , 2.36 , 12.19) | (-4.02 , -0.43 , -0.06) | (-2.93 , -0.25 , -0.05) | (0.03 , 0.41 , 9.19) | (-4.01 , -0.13 , -0.02) | (0.02 , 0.15 , 4.56) |
| PS02 | Contact tunnel dryer | (-4.44 , -0.56 , -0.1) | (0.21 , 1.73 , 9.14) | (-4.02 , -0.43 , -0.06) | (-2.93 , -0.25 , -0.05) | (0.03 , 0.41 , 9.19) | (-4.01 , -0.13 , -0.02) | (0.02 , 0.15 , 4.56) |
| PS03 | Plate dryer | (-4.44 , -0.56 , -0.1) | (0.3 , 2.36 , 12.19) | (-4.02 , -0.43 , -0.06) | (-8.78 , -0.76 , -0.08) | (0.05 , 1.23 , 27.58) | (-4.01 , -0.13 , -0.02) | (0.02 , 0.15 , 4.56) |
| PS04 | Contact conveyor dryers | (-4.44 , -0.56 , -0.1) | (0.21 , 1.73 , 9.14) | (-4.02 , -0.43 , -0.06) | (-8.78 , -0.76 , -0.08) | (0.05 , 1.23 , 27.58) | (-4.01 , -0.13 , -0.02) | (0.03 , 0.46 , 13.69) |
| PS05 | Rotary steam tube dryer | (-4.45 , -0.55 , -0.1) | (0.45 , 3 , 13.71) | (-6.7 , -1.29 , -0.19) | (-14.64 , -2.28 , -0.23) | (0.05 , 1.23 , 27.58) | (-12.03 , -0.4 , -0.03) | (0.08 , 1.39 , 22.82) |
| PS06 | Drum dryer | (-4.52 , -0.56 , -0.1) | (0.42 , 2.82 , 12.95) | (-6.7 , -2.14 , -0.57) | (-8.78 , -0.76 , -0.08) | (0.05 , 1.23 , 27.58) | (-4.01 , -0.13 , -0.02) | (0.03 , 0.46 , 13.69) |
| PS07 | Direct cabinet dryer | (-11.91 , -0.69 , -0.04) | (0.3 , 2.36 , 12.19) | (-1.34 , -0.14 , -0.04) | (-2.93 , -0.25 , -0.05) | (0.03 , 0.41 , 9.19) | (-12.03 , -0.4 , -0.03) | (0.02 , 0.15 , 4.56) |
| PS08 | Direct tunnel dryer | (-11.91 , -0.69 , -0.04) | (0.21 , 1.36 , 6.1) | (-1.34 , -0.14 , -0.04) | (-2.93 , -0.25 , -0.05) | (0.03 , 0.41 , 9.19) | (-12.03 , -0.4 , -0.03) | (0.03 , 0.46 , 13.69) |
| PS09 | Direct conveyor dryers | (-11.91 , -0.69 , -0.04) | (0.21 , 1.73 , 9.14) | (-1.34 , -0.14 , -0.04) | (-8.78 , -0.76 , -0.08) | (0.05 , 1.23 , 27.58) | (-12.03 , -0.4 , -0.03) | (0.03 , 0.46 , 13.69) |
| PS10 | Chamber/bin dryer | (-11.91 , -0.69 , -0.04) | (0.21 , 1.36 , 6.1) | (-1.34 , -0.14 , -0.04) | (-2.93 , -0.25 , -0.05) | (0.05 , 1.23 , 27.58) | (-12.03 , -0.4 , -0.03) | (0.03 , 0.46 , 13.69) |

a) Base-cased normalization

| PROCESSING SUBSYSTEM | | SUB-CRITERIA | | | | | | |
|---|---|---|---|---|---|---|---|---|
| ID | Technology | $C_{11}$ | $C_{12}$ | $C_{21}$ | $C_{22}$ | $C_{31}$ | $C_{32}$ | $C_{33}$ |
| PSbc | Fluidized bed dryer | (-9.6 , -0.84 , -0.1) | (0.19 , 1.93 , 13.69) | (-6.38 , -0.56 , -0.06) | (-11.95 , -1.7 , -0.19) | (0.05 , 1.49 , 36.75) | (-16.36 , -0.49 , -0.03) | (0.03 , 0.53 , 17.46) |
| PS01 | Contact cabinet dryer | (-3.47 , -0.44 , -0.08) | (0.28 , 2.44 , 13.73) | (-6.38 , -0.56 , -0.06) | (-2.39 , -0.19 , -0.04) | (0.03 , 0.5 , 12.25) | (-5.45 , -0.16 , -0.02) | (0.02 , 0.18 , 5.82) |
| PS02 | Contact tunnel dryer | (-3.47 , -0.44 , -0.08) | (0.19 , 1.79 , 10.3) | (-6.38 , -0.56 , -0.06) | (-2.39 , -0.19 , -0.04) | (0.03 , 0.5 , 12.25) | (-5.45 , -0.16 , -0.02) | (0.02 , 0.18 , 5.82) |
| PS03 | Plate dryer | (-3.47 , -0.44 , -0.08) | (0.28 , 2.44 , 13.73) | (-6.38 , -0.56 , -0.06) | (-7.17 , -0.57 , -0.06) | (0.05 , 1.49 , 36.75) | (-5.45 , -0.16 , -0.02) | (0.02 , 0.18 , 5.82) |
| PS04 | Contact conveyor dryers | (-3.47 , -0.44 , -0.08) | (0.19 , 1.79 , 10.3) | (-6.38 , -0.56 , -0.06) | (-7.17 , -0.57 , -0.06) | (0.05 , 1.49 , 36.75) | (-5.45 , -0.16 , -0.02) | (0.03 , 0.53 , 17.46) |
| PS05 | Rotary steam tube dryer | (-3.47 , -0.44 , -0.08) | (0.41 , 3.1 , 15.45) | (-10.64 , -1.68 , -0.19) | (-11.95 , -1.7 , -0.19) | (0.05 , 1.49 , 36.75) | (-16.36 , -0.49 , -0.03) | (0.08 , 1.58 , 29.09) |
| PS06 | Drum dryer | (-3.53 , -0.44 , -0.08) | (0.39 , 2.91 , 14.59) | (-10.64 , -2.8 , -0.57) | (-7.17 , -0.57 , -0.06) | (0.05 , 1.49 , 36.75) | (-5.45 , -0.16 , -0.02) | (0.03 , 0.53 , 17.46) |
| PS07 | Direct cabinet dryer | (-9.29 , -0.55 , -0.04) | (0.28 , 2.44 , 13.73) | (-2.13 , -0.19 , -0.04) | (-2.39 , -0.19 , -0.04) | (0.03 , 0.5 , 12.25) | (-16.36 , -0.49 , -0.03) | (0.02 , 0.18 , 5.82) |
| PS08 | Direct tunnel dryer | (-9.29 , -0.55 , -0.04) | (0.19 , 1.41 , 6.86) | (-2.13 , -0.19 , -0.04) | (-2.39 , -0.19 , -0.04) | (0.03 , 0.5 , 12.25) | (-16.36 , -0.49 , -0.03) | (0.03 , 0.53 , 17.46) |
| PS09 | Direct conveyor dryers | (-9.29 , -0.55 , -0.04) | (0.19 , 1.79 , 10.3) | (-2.13 , -0.19 , -0.04) | (-7.17 , -0.57 , -0.06) | (0.05 , 1.49 , 36.75) | (-16.36 , -0.49 , -0.03) | (0.03 , 0.53 , 17.46) |

Figure 4-11. Normalization of the judgment data of the alternatives

Figure 4-12 shows the local weights of the criteria and sub-criteria calculated from the previous reciprocal matrices (values $w_j$ and $w_{jk}$ respectively).

| Local weigh of criteria (level 2) | | Local weight of sub-criteria (level 3) | |
|---|---|---|---|
| C1 | (0.31 , 1.24 , 4.3) | C11 | (0.2 , 1 , 5) |
| | | C12 | (0.2 , 1 , 5) |
| | | C13 | (0.2 , 1 , 5) |
| | | C14 | (0.2 , 1 , 5) |
| C2 | (0.24 , 0.88 , 3.52) | C21 | (0.58 , 1 , 1.73) |
| | | C22 | (0.58 , 1 , 1.73) |
| C3 | (0.24 , 0.88 , 3.52) | C31 | (0.31 , 1.24 , 4.3) |
| | | C32 | (0.24 , 0.88 , 3.52) |
| | | C33 | (0.24 , 0.88 , 3.52) |

Figure 4-12. Normalization of the judgment data of criteria and sub-criteria

#### 4.2.2.4 Aggregate the ratings of alternative over the hierarchy

Global weights of the alternatives are subsequently aggregated along the hierarchy using the equations presented in Section 3.4.2.3. The data sheets below step-by-step represent the computation of the global weights of the processing technology alternatives (the case of aggregated normalization).

a) Relative weights of alternatives with respect to the criteria (values $r_{ij}$)

| PROCESSING SUBSYSTEM | | CRITERIA | | |
|---|---|---|---|---|
| ID | Technology | $C_1$ | $C_2$ | $C_3$ |
| PS01 | Contact cabinet dryer | (-2.07 , 0.9 , 6.05) | (-3.47 , -0.34 , -0.05) | (-1.32 , 0.14 , 4.58) |
| PS02 | Contact tunnel dryer | (-2.12 , 0.58 , 4.52) | (-3.47 , -0.34 , -0.05) | (-1.32 , 0.14 , 4.58) |
| PS03 | Plate dryer | (-2.07 , 0.9 , 6.05) | (-6.4 , -0.59 , -0.07) | (-1.32 , 0.42 , 10.71) |
| PS04 | Contact conveyor dryers | (-2.12 , 0.58 , 4.52) | (-6.4 , -0.59 , -0.07) | (-1.31 , 0.52 , 13.75) |
| PS05 | Rotary steam tube dryer | (-2 , 1.22 , 6.81) | (-10.67 , -1.78 , -0.21) | (-3.97 , 0.74 , 16.79) |
| PS06 | Drum dryer | (-2.05 , 1.13 , 6.43) | (-7.74 , -1.45 , -0.32) | (-1.31 , 0.52 , 13.75) |
| PS07 | Direct cabinet dryer | (-5.8 , 0.84 , 6.07) | (-2.13 , -0.2 , -0.04) | (-3.99 , 0.05 , 4.58) |
| PS08 | Direct tunnel dryer | (-5.85 , 0.34 , 3.03) | (-2.13 , -0.2 , -0.04) | (-3.99 , 0.16 , 7.62) |
| PS09 | Direct conveyor dryers | (-5.85 , 0.52 , 4.55) | (-5.06 , -0.45 , -0.06) | (-3.98 , 0.43 , 13.75) |
| PS10 | Chamber/bin dryer | (-5.85 , 0.34 , 3.03) | (-2.13 , -0.2 , -0.04) | (-3.98 , 0.43 , 13.75) |

b) Global weights of alternatives with respect to the overall objective (value $r_i$)

| PROCESSING SUBSYSTEM | | OVERALL OBJECTIVE |
|---|---|---|
| ID | Technology | O |
| PS01 | Contact cabinet dryer | (-0.65 , 0.5 , 14.69) |
| PS02 | Contact tunnel dryer | (-0.65 , 0.31 , 11.93) |
| PS03 | Plate dryer | (-0.86 , 0.51 , 19.73) |
| PS04 | Contact conveyor dryers | (-0.87 , 0.34 , 19.48) |
| PS05 | Rotary steam tube dryer | (-1.35 , 0.53 , 26.01) |
| PS06 | Drum dryer | (-0.95 , 0.49 , 22.72) |
| PS07 | Direct cabinet dryer | (-1.28 , 0.47 , 14.75) |
| PS08 | Direct tunnel dryer | (-1.28 , 0.19 , 11.73) |
| PS09 | Direct conveyor dryers | (-1.5 , 0.31 , 19.53) |
| PS10 | Chamber/bin dryer | (-1.28 , 0.25 , 16.78) |

Figure 4-13. Aggregate the weightings of alternatives along the hierarchy

#### 4.2.2.5 Rating and ranking of the subsystem technologies

The results of the rating and ranking process from the previous steps are the global weights of the alternatives along the hierarchy in the form of TFNs. In order to facilitate the final decision, they are transformed to crisp numbers through a defuzzification process. Figure 4-14 views a part of the data sheet computed for this defuzzification process using centroid point method. The data in column "Ranking" presents the ascending order of the selected processing technology alternatives. The smaller the order numbers of the alternative, the more referable the alternative in terms of sustainability.

| PROCESSING SUBSYSTEM | | FUZZY RATING | DEFFUZIFICATION | | | RANKING |
|---|---|---|---|---|---|---|
| ID | Technology | $r_{PS}$ | $x_{PS}$ | $y_{PS}$ | $R_{PS}$ | |
| PS01 | Contact cabinet dryer | (-0.65 , 0.5 , 14.69) | 4.8500 | 0.3560 | 4.8630 | 12 |
| PS02 | Contact tunnel dryer | (-0.65 , 0.31 , 11.93) | 3.8630 | 0.3510 | 3.8790 | 15 |
| PS03 | Plate dryer | (-0.86 , 0.51 , 19.73) | 6.4600 | 0.3500 | 6.4690 | 8 |
| PS04 | Contact conveyor dryers | (-0.87 , 0.34 , 19.48) | 6.3160 | 0.3450 | 6.3250 | 9 |
| PS05 | Rotary steam tube dryer | (-1.35 , 0.53 , 26.01) | 8.3950 | 0.3470 | 8.4020 | 3 |
| PS06 | Drum dryer | (-0.95 , 0.49 , 22.72) | 7.4210 | 0.3480 | 7.4290 | 5 |
| PS07 | Direct cabinet dryer | (-1.28 , 0.47 , 14.75) | 4.6480 | 0.3550 | 4.6620 | 14 |
| PS08 | Direct tunnel dryer | (-1.28 , 0.19 , 11.73) | 3.5470 | 0.3450 | 3.5640 | 16 |
| PS09 | Direct conveyor dryers | (-1.5 , 0.31 , 19.53) | 6.1140 | 0.3440 | 6.1240 | 10 |
| PS10 | Chamber/bin dryer | (-1.28 , 0.25 , 16.78) | 5.2500 | 0.3440 | 5.2610 | 11 |

Figure 4-14. Defuzzification - ranking of the subsystem technology alternatives

### 4.2.3 Rating and ranking of the system technologies

#### 4.2.3.1 Important factors of the subsystems

The important factors of the subsystems are determined by the comparative justification method, analogously to the determination of the weightings of the criteria. The processing subsystem is the core component of the drying process, thus it should be given a higher priority than the heating subsystem and heat recovery subsystem

Figure 4-15 shows the pairwise comparison and the reciprocal matrix for determining the important factors of the dryer subsystems.

| SUBSYSTEM | | PAIR WISE COMPARISON MATRIX | | | RECIPROCAL MATRIX | | | IMPORTANT FACTOR |
|---|---|---|---|---|---|---|---|---|
| ID | Subsystem | PS | HS | RS | PS | HS | RS | |
| PS | Processing subsystem | EQ | H | VH | (1 , 1 , 1) | (1 , 3 , 5) | (3 , 5 , 5) | (5 , 0.738 , 1.816) |
| HS | Heating subsystem | | EQ | H | (0.2 , 0.33 , 1) | (1 , 1 , 1) | (1 , 3 , 5) | (5 , 0.325 , 0.874) |
| RS | Heat recovery subsystem | | | EQ | (0.2 , 0.2 , 0.33) | (0.2 , 0.33 , 1) | (1 , 1 , 1) | (1 , 0.207 , 0.309) |

Figure 4-15. The reciprocal matrix and important factors of the dryer subsystems

#### 4.2.3.2 Rating of the system technologies

Ratings of the system technologies are calculated from the ratings of the modular subsystems by Equation 3-11 and programmed as in the spreadsheet in Figure 4-16.

| SYSTEM ALTERNATIVE | | SUBSYSTEM | | | FUZZY RATING OF THE SUBSYSTEM | | | FUZZY RATING OF THE SYSTEM |
|---|---|---|---|---|---|---|---|---|
| ID | Technology | PS | HS | RS | $r_{PS}$ | $r_{HS}$ | $r_{RS}$ | $r_A$ |
| A055 | Contact conveyor dryers - Boiler/hea | PS04 | HS01 | RS01 | (-0.87 , 0.34 , 19.48) | (-1.38 , 0.58 , 25.72) | (-0.2 , 0.21 , 16.78) | (-0.38 , 0.39 , 50.4) |
| A058 | Contact conveyor dryers - Boiler-ren | PS04 | HS02 | RS01 | (-0.87 , 0.34 , 19.48) | (-1.36 , 0.94 , 31.4) | (-0.2 , 0.21 , 16.78) | (-0.37 , 0.5 , 55.02) |
| A061 | Contact conveyor dryers - Boiler-mix | PS04 | HS03 | RS01 | (-0.87 , 0.34 , 19.48) | (-1.38 , 0.71 , 24.51) | (-0.2 , 0.21 , 16.78) | (-0.38 , 0.43 , 49.42) |
| A073 | Rotary steam tube dryer - Boiler/heat | PS05 | HS01 | RS01 | (-1.35 , 0.53 , 26.01) | (-1.38 , 0.58 , 25.72) | (-0.2 , 0.21 , 16.78) | (-0.5 , 0.51 , 58.76) |
| A076 | Rotary steam tube dryer - Boiler-rene | PS05 | HS02 | RS01 | (-1.35 , 0.53 , 26.01) | (-1.36 , 0.94 , 31.4) | (-0.2 , 0.21 , 16.78) | (-0.49 , 0.61 , 63.38) |
| A079 | Rotary steam tube dryer - Boiler-mixe | PS05 | HS03 | RS01 | (-1.35 , 0.53 , 26.01) | (-1.38 , 0.71 , 24.51) | (-0.2 , 0.21 , 16.78) | (-0.5 , 0.55 , 57.78) |
| A145 | Direct conveyor dryers - Boiler/heate | PS09 | HS01 | RS01 | (-1.5 , 0.31 , 19.53) | (-1.38 , 0.58 , 25.72) | (-0.2 , 0.21 , 16.78) | (-0.53 , 0.38 , 50.47) |
| A146 | Direct conveyor dryers - Boiler/heate | PS09 | HS01 | RS02 | (-1.5 , 0.31 , 19.53) | (-1.38 , 0.58 , 25.72) | (-1.14 , 0.58 , 42.2) | (-0.6 , 0.41 , 57.37) |
| A147 | Direct conveyor dryers - Boiler/heate | PS09 | HS01 | RS03 | (-1.5 , 0.31 , 19.53) | (-1.38 , 0.58 , 25.72) | (-1.25 , 0.17 , 33.05) | (-0.6 , 0.37 , 54.89) |
| A148 | Direct conveyor dryers - Boiler-renev | PS09 | HS02 | RS01 | (-1.5 , 0.31 , 19.53) | (-1.36 , 0.94 , 31.4) | (-0.2 , 0.21 , 16.78) | (-0.53 , 0.48 , 55.1) |
| A149 | Direct conveyor dryers - Boiler-renev | PS09 | HS02 | RS02 | (-1.5 , 0.31 , 19.53) | (-1.36 , 0.94 , 31.4) | (-1.14 , 0.58 , 42.2) | (-0.59 , 0.52 , 61.99) |
| A150 | Direct conveyor dryers - Boiler-renev | PS09 | HS02 | RS03 | (-1.5 , 0.31 , 19.53) | (-1.36 , 0.94 , 31.4) | (-1.25 , 0.17 , 33.05) | (-0.6 , 0.48 , 59.51) |
| A151 | Direct conveyor dryers - Boiler-mixe | PS09 | HS03 | RS01 | (-1.5 , 0.31 , 19.53) | (-1.38 , 0.71 , 24.51) | (-0.2 , 0.21 , 16.78) | (-0.53 , 0.42 , 49.49) |
| A152 | Direct conveyor dryers - Boiler-mixe | PS09 | HS03 | RS02 | (-1.5 , 0.31 , 19.53) | (-1.38 , 0.71 , 24.51) | (-1.14 , 0.58 , 42.2) | (-0.6 , 0.45 , 56.39) |
| A153 | Direct conveyor dryers - Boiler-mixe | PS09 | HS03 | RS03 | (-1.5 , 0.31 , 19.53) | (-1.38 , 0.71 , 24.51) | (-1.25 , 0.17 , 33.05) | (-0.6 , 0.41 , 53.9) |
| A154 | Direct conveyor dryers - Solar collec | PS09 | HS04 | RS01 | (-1.5 , 0.31 , 19.53) | (-1.45 , 0.37 , 17.8) | (-0.2 , 0.21 , 16.78) | (-0.54 , 0.31 , 44.02) |
| A157 | Direct conveyor dryers - Heat pump | PS09 | HS05 | RS01 | (-1.5 , 0.31 , 19.53) | (-0.43 , 1.01 , 28.51) | (-0.2 , 0.21 , 16.78) | (-0.43 , 0.5 , 52.74) |
| A181 | Direct rotary dryer - Boiler/heater-no | PS11 | HS01 | RS01 | (-1.82 , 0.27 , 23.32) | (-1.38 , 0.58 , 25.72) | (-0.2 , 0.21 , 16.78) | (-0.61 , 0.36 , 55.31) |
| A182 | Direct rotary dryer - Boiler/heater-no | PS11 | HS01 | RS02 | (-1.82 , 0.27 , 23.32) | (-1.38 , 0.58 , 25.72) | (-1.14 , 0.58 , 42.2) | (-0.68 , 0.39 , 62.21) |

Figure 4-16. Fuzzy ratings of the system technologies

#### 4.2.3.3 Ranking of the system technologies

Rankings of the system technologies are also defined by centroid point method as shown in Equations 3-8 to 3-10.

| SYSTEM ALTERNATIVE | | SUBSYSTEM | | | FUZZY RATING OF THE SYSTEM | DEFFUZIFICATION | | | RANKING |
|---|---|---|---|---|---|---|---|---|---|
| ID | Technology | PS | HS | RS | $r_A$ | $x_A$ | $y_A$ | $R_A$ | |
| A055 | Contact conveyor dryers - Boiler/hea | PS04 | HS01 | RS01 | (-0.38 , 0.39 , 50.4) | 16.81 | 0.34 | 16.81 | 75 |
| A058 | Contact conveyor dryers - Boiler-ren | PS04 | HS02 | RS01 | (-0.37 , 0.5 , 55.02) | 18.38 | 0.34 | 18.39 | 56 |
| A061 | Contact conveyor dryers - Boiler-mix | PS04 | HS03 | RS01 | (-0.38 , 0.43 , 49.42) | 16.49 | 0.34 | 16.50 | 80 |
| A073 | Rotary steam tube dryer - Boiler/heat | PS05 | HS01 | RS01 | (-0.5 , 0.51 , 58.76) | 19.59 | 0.34 | 19.59 | 40 |
| A076 | Rotary steam tube dryer - Boiler-rene | PS05 | HS02 | RS01 | (-0.49 , 0.61 , 63.38) | 21.17 | 0.34 | 21.17 | 23 |
| A079 | Rotary steam tube dryer - Boiler-mixe | PS05 | HS03 | RS01 | (-0.5 , 0.55 , 57.78) | 19.28 | 0.34 | 19.28 | 47 |
| A145 | Direct conveyor dryers - Boiler/heate | PS09 | HS01 | RS01 | (-0.53 , 0.38 , 50.47) | 16.77 | 0.34 | 16.78 | 76 |
| A146 | Direct conveyor dryers - Boiler/heate | PS09 | HS01 | RS02 | (-0.6 , 0.41 , 57.37) | 19.06 | 0.34 | 19.07 | 49 |
| A147 | Direct conveyor dryers - Boiler/heate | PS09 | HS01 | RS03 | (-0.6 , 0.37 , 54.89) | 18.22 | 0.34 | 18.22 | 59 |
| A148 | Direct conveyor dryers - Boiler-renev | PS09 | HS02 | RS01 | (-0.53 , 0.48 , 55.1) | 18.35 | 0.34 | 18.35 | 58 |
| A149 | Direct conveyor dryers - Boiler-renev | PS09 | HS02 | RS02 | (-0.59 , 0.52 , 61.99) | 20.64 | 0.34 | 20.64 | 28 |
| A150 | Direct conveyor dryers - Boiler-renev | PS09 | HS02 | RS03 | (-0.6 , 0.48 , 59.51) | 19.79 | 0.34 | 19.80 | 36 |
| A151 | Direct conveyor dryers - Boiler-mixe | PS09 | HS03 | RS01 | (-0.53 , 0.42 , 49.49) | 16.46 | 0.34 | 16.46 | 82 |
| A152 | Direct conveyor dryers - Boiler-mixe | PS09 | HS03 | RS02 | (-0.6 , 0.45 , 56.39) | 18.75 | 0.34 | 18.75 | 51 |
| A153 | Direct conveyor dryers - Boiler-mixe | PS09 | HS03 | RS03 | (-0.6 , 0.41 , 53.9) | 17.90 | 0.34 | 17.91 | 62 |
| A154 | Direct conveyor dryers - Solar collec | PS09 | HS04 | RS01 | (-0.54 , 0.31 , 44.02) | 14.60 | 0.34 | 14.60 | 98 |
| A157 | Direct conveyor dryers - Heat pump | PS09 | HS05 | RS01 | (-0.43 , 0.5 , 52.74) | 17.61 | 0.34 | 17.61 | 67 |
| A181 | Direct rotary dryer - Boiler/heater-no | PS11 | HS01 | RS01 | (-0.61 , 0.36 , 55.31) | 18.35 | 0.34 | 18.36 | 57 |
| A182 | Direct rotary dryer - Boiler/heater-no | PS11 | HS01 | RS02 | (-0.68 , 0.39 , 62.21) | 20.64 | 0.34 | 20.65 | 27 |

Figure 4-17. Ranking of the system technologies

## 4.3 EVALUATION OF DRYING TECHNOLOGIES CONSIDERING SUSTAINABILITY OF THE PROCESS

As discussed in Section 3.4.1, the evaluation and selection of food drying technologies should be based on three main criteria: Environmental, economic and social performance. Each criterion is decomposed to sub-criteria as follows:

Table 4-2. Criteria for the evaluation and selection of food drying technologies considering sustainability of the process

| ***Criteria*** | ***Sub-criteria*** | ***Description*** |
|---|---|---|
| Environmental performance | Specific thermal energy requirement | The unit thermal energy consumption for the evaporation of 1 kg of moisture |
| | Thermal efficiency | Heat utilized in moisture evaporation divided by the total heat input |
| | Energy recovery ratio | Ratio of the recovered energy in the exhaust air and the total energy consumption of the drying process |
| | Renewable energy usage | Ratio of the renewable energy consumption and the total energy consumption for the process |
| Economic performance | Investment cost | Including purchased cost, costs of equipment installation, costs of piping and instrumentation |
| | Operation cost | Including energy cost, capital cost, labour cost and maintenance cost |
| Social performance | Final product quality | Quality of final product concerning physical, chemical and nutritional quality |
| | Fire hazard and explosion hazard | Risk of fire and explosion during the operation of the drying process |
| | Convenience of installation and operation | The compromise of different parameters during the installation phase (floor area) and operation phase of the drying equipment (maintenance requirement, ease of control, drying time) |

A database containing the performance data of the drying technologies has been created based on the information available in the literature and the practical experiences. The following parts present the data with respect to the previous criteria that will be used in the rating and ranking process and how they have been recorded in the database.

### 4.3.1 Environmental performance

Environmental performance of a drying process mostly involves the air pollution and the high energy consumption. Drying is one of the most energy-intensive unit operations in food processing industry. Studies claimed that the national energy consumption for industrial drying operations ranging from 10 - 15% for USA, Canada, France, and UK to 20 - 25% for Denmark and Germany (Mujumdar & Devahastin, 2000). Ciesielski and Zbicinski (2010) showed that in the operation stage of spray dryers, the main effect on the environment is the massive usage of energy to heat up a drying agent. Energy cost is therefore the largest operating expense of a drying system on the one hand and energy performance is one of the most important evaluation criteria in the selection of food drying systems on the other hand.

For this reason, in order to promote sustainability of the drying process, energy performance is particularly considered in this study. Generally, energy use in the drying process involves two main types: 1) thermal energy for heating up the material from initial temperature to exit temperature and for evaporating the water that leaves the material and 2) electrical energy for mechanical devices such as fans, blowers, material conveyors, vibrators, etc. Many studies reported very small figures of energy demand for mechanical operations compared to thermal operations. According to a study by Wetchacama et al. (2000), energy for the mechanical operations account for 12.6 - 14% of total energy consumption of the drying process. For this reason, energy for thermal operations is merely taken into consideration of this study, energy for mechanical operation is excluded from the appraisal of energy performance of the drying process.

The parameters for evaluation of drying energy performance generally consist of energy utilization, energy efficiency, exergy efficiency, amongst others. Table 4-3 provides an overview of parameters commonly used.

Table 4-3. Common parameters for the evaluation of energy performance of drying process

| ***Parameter*** | ***Description*** |
|---|---|
| Specific energy requirement | Unit energy consumption for the evaporation of 1 kg of moisture |
| Energy utilization | Total energy consumption for drying in a period of time |
| Steam consumption | Measurement of energy consumption for the drying process in the steam-based systems |
| Dryer efficiency | Ratio of total heat utilized for drying to total heat input |
| Thermal efficiency | Ratio of heat utilized in moisture evaporation divided by the total heat input |
| Evaporative efficiency | Ratio of actual heat used in evaporation and the amount of heat needed for maximum possible evaporation of water in the wet product |
| Coefficient of Performance (COP) | The ratio of the output heat of the heat pump system to the supplied work |
| Exergy efficiency | Ratio of exergy use in the drying of the product to the exergy of the drying air supplied to the system |
| Exergy loss | Difference of exergy input and exergy output of drying process |
| Specific moisture evaporation rate (SMER) | Ratio of total moisture removed to the total energy input |
| Dryer efficiency factor (DEF) | Ratio of the experimentally measured energy efficiency to simulated operation energy efficiency |

In this study, parameters related to specific thermal energy consumption (STEC), thermal efficiency, ratio of heat recovery and ratio of renewable energy utilization have been utilized in the appraisal of energy performance of the drying process. Since energy performance plays the most important role in the selection process, it requires adequate estimation. Section 4.4 introduces the models developed for the estimation of STEC of various dryer types and the data recorded for the performances with respect to thermal efficiency, ratio of heat recovery and ratio of renewable energy utilization.

### 4.3.2 Economic performance

In practice, dryer selection decisions are frequently made on the basis of initial investment cost. However, operating cost, which dominated by expenditure on energy consumption accounts for a large portion of the total cost over the lifetime of a typical dryer (Baker, 1997).

#### 4.3.2.1 Investment cost

Total investment cost should include purchase cost, costs of equipment installation, costs of piping and instrumentation. Reliable investment cost data for industrial dryers can be obtained from suppliers. However, to aid the price quotation, data for the particular application should be provided in details. Consequently, Craptiste and Rotstein (1997), Baker (1997), Imre (1997), Sokhasanj (1997), Snowman (1997), Saravacos and Kostaropoulou (2002), Sztabert and Kudra (2006), Mani and Sokhansanj (2008) have provided models of cost estimation of various dryer types. In general, the estimation of dryer investment cost can be made from the following bases:

- Known cost of the equipment or system previously built;
- Dryer capacity in terms of effective volume or surface area;
- Evaporation capacity of dryer and inlet air temperature.

As comparative evaluations, investment costs of contact dryers are obviously higher than that of hot air dryers; vacuum dryers are more costly than dryers operating at atmospheric pressure; and the greater the dryer capacity, the smaller the investment costs. According to a review by Craptiste and Rotstein (1997), tray and tunnel dryers have the lowest prices, followed by conveyor dryers, belt-through and vibrated-bed systems increase the investment costs. Rotary dryers have higher unit cost but still it is lower than drum dryers. Within the range of 1 - 50 Mt/year, rotary, fluidized bed and pneumatic dryers cost about the same (Couper et al., 2005).

Compared to hot air dryers, heat pump dryers require higher initial investment but present a better cost-effectiveness due to a more efficient energy usage (Perera & Rahma, 1997). Once-through air dryers are one-half as expensive as recirculating gas equipment (Couper et al., 2005). Capital cost of freeze dryers can be about three times those of other methods (Snowman, 1997). Vacuum freeze dryers are amongst the dryers of highest investment costs, 4 - 8 times as high as conventional hot air systems (Ratti, 2001), followed by spray dryers (Mujumdar & Canmet, 2001).

#### 4.3.2.2 Operation cost

Operation costs consist of energy cost, capital cost, labor cost and maintenance cost. Capital cost of many dryer types is responsible for less than 10% of the total (Baker, 1997), the largest portion comes from expenditure for energy consumption. This is very typical for a large number of conventional dryer types including tray and tunnel dryer, rotary dryer, fluid bed dryer, pneumatic dryer, and so on. However, for some specific dryer types, energy cost makes up a rather small portion compared to other costs. An example of this can be seen in Figure 4-18. In this figure, the breakdowns of annual operation costs of a vibro fluid bed dryer and a freeze dryer are compared. In the vibrio fluid bed dryer, the operation cost is responsible for up to 61.2% of the total annual operation cost while in the freeze dryer, the largest portion (59.3%) comes from the capital cost.

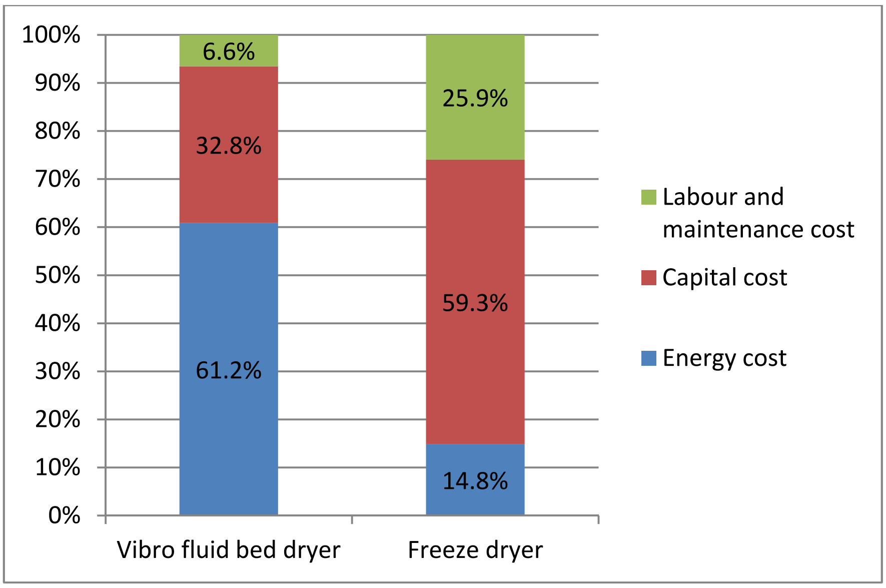


Figure 4-18. Breakdowns of annual operation costs of vibro fluid bed dryer and freeze dryer (data taken from Wetchacama et al. (2000) and Ratti (2001))

A rough comparative evaluation given by Crapiste and Rotstein (1997) shows that air drying in cabinet or tunnel dryers have the lowest operation cost. Conveyor, drum, and pneumatic drying systems are also of relatively low cost. Fluid bed and spray drying are more costly and can reach twice the cost of forced air drying. Many studies claimed freeze drying is the most expensive way of food dehydration, up to 3 times as high as the conventional air drying (Snowman, 1997).

A qualitative evaluation of investment cost and operation cost of various dryer types using the linguistic scale as described in Section 3.4.2.1 is shown in Table 4-4. This data will be used for the appraisal of economic performance of the drying technologies in the rating and ranking process.

Table 4-4. Evaluation of economic performance of common food dryers

| ***Dryer type*** | ***Investment cost*** | ***Operation cost*** |
|---|---|---|
| Contact cabinet dryer | M | L |
| Contact tunnel dryer | M | L |
| Plate dryer | M | M |
| Contact conveyor dryers | M | M |
| Rotary steam tube dryer | H | H |
| Drum dryer | VH | M |
| Direct cabinet dryer | L | L |
| Direct tunnel dryer | L | L |
| Direct conveyor dryers | L | M |
| Chamber/bin dryer | L | L |
| Direct rotary dryer | M | H |
| Fluidized bed dryer | M | H |
| Spouted bed dryer | M | H |
| Spray dryer | VH | H |

| ***Dryer type*** | ***Investment cost*** | ***Operation cost*** |
|---|---|---|
| Pneumatic flash dryer | M | M |
| Freeze dryer | VH | VH |

### 4.3.3 Social performance

#### 4.3.3.1 Product quality

Product quality is always of greatest concern when selecting the type of dryer to be used. Quality attributes of the finished product determine the drying parameters to be established for the drying process. Perera and Rahman (2008) classified quality parameters of dried food products into 3 groups:

- Physical quality: Structure, case hardening, collapse, pore formation, cracking, rehydration, caking and stickiness;
- Chemical quality: Browning, lipid oxidation, color loss and change of favor;
- Nutritional quality: Nutritional quality of food products are mainly characterized by the retention of vitamin, mineral, protein etc.

According to Mujumdar (1997), most of the above quality properties are not readily quantified and a few can be measured on-line for control purposes.

Quality properties of dried food are significantly affected by the drying methods and the process conditions. Thus, the same raw material may end up as a completely different product, depending on the type of drying method and the drying parameters applied (Tín, 2006). Changes of the processing parameters during drying may also result in variation of product quality. In general, under the same conditions, the lower the temperature of the drying process, the better the quality of the product (Barta, 2006).

Parameters that can cause significant impacts on product quality in various drying methods are:

- Sun and solar drying: drying time and drying temperature
- Hot air drying: air temperature, air humidity, air velocity
- Contact drying: contact surface temperature (effected by steam pressure)

- Vacuum drying: pressure, air temperature
- Freeze drying: applied pressure

Mujumdar (1997) noted that in addition to drying conditions, food quality is also affected by other non-drying parameters like pH, composition of the food, feed pretreatments and the presence of salts, solvents and oils. Krokida and Maroulis (2000) compiled a large number of data concerning quality changes in terms of structural, optical (color), texture properties during drying of various food products.

Table 4-5. Review of studies on dried product quality performance

| ***Dryer type*** | ***Food product*** | ***Important observation*** | ***Reference*** |
|---|---|---|---|
| Hot air drying | Durian slices | Durian slices dried at higher temperatures had higher rehydration capacity than those dried at lower temperatures. | Jamaradloedluk et al. (2007) |
| Spray dryer | Gooseberry powder | Increase in the inlet drying temperature results in a lower vitamin C content | Thankitsunthor et al. (2005) |
| Hot air dryer | Okra fruit | High drying temperatures has negative effect on the color, ascorbic acid and viscosity of okra. | Inyand and Ike (1998) |
| Convective dryer | Red bell pepper | The higher the drying temperature, the lesser the stability of the color pigments.<br>The air drying temperature had a detrimental effect on the retention of ascorbic acid. | Vega-Gálvez et al. (2008) |
| Batch fluid bed dryer | Chopped coconut pieces | Color parameter was affected mostly by the inlet air temperature, while the quantity of surface oil was affected mostly by the inlet air velocity.<br>Drying with high inlet air temperatures led to a product of darker color, while drying with high inlet air velocity led to a product of higher surface oil content | Niamnuy and Devahastin (2005) |

| ***Dryer type*** | ***Food product*** | ***Important observation*** | ***Reference*** |
|---|---|---|---|
| Fluid bed dryer | White button mushroom slices | Color index, ascorbic acid content, water activity and rehydration ratio decreased with increase drying air temperature | Murumkar et al. (2006) |
| Fluid bed dryer | Rice | The whiteness is slightly decreased with increase in drying air temperature and initial moisture content. | Tirawanichakul et al. (2004) |
| Spray dryer | Orange juice concentrate | Moisture content decreases with an increase in inlet air temperature and a decrease in maltodextrin concentration<br>Rehydration ability increases with an increase in inlet air temperature and maltodextrin concentration | Goula and Adamopoulos (2010) |
| Heat pump dryer | Green sweet pepper | The quality parameters showed a declining trend with increase in drying air temperature. | Pal et al. (2008) |
| Drum dryer | Jackfruit puree | Moisture content and water activity decrease with increasing the drum temperature | Pua et al. (2010) |

Some comparative observations on the trend of product quality processed in various drying methods:

- Although air drying is the most popular technique for food preservation, it is considered to give less satisfactory product quality than the other methods, both with respect to the nutritional value and to the sensory properties such as texture, color and flavor (Nijhuis et al., 1998).
- Sensory quality of air-dried products is generally less acceptable than the freeze-dried ones (Leino, 1992; Sinesio et al., 1995).
- The sun-dried vegetables have inferior color, texture and acceptability compared to the vegetables dried in the cabinet dryer (Onayemi & Badifu, 1987)
- Freeze drying has been proved to end up with final product of highest quality regards to physical, chemical and nutritional properties (Krokida & Maroulis, 2000; Ratti, 2001;

Grabowski et al., 2002; Nindo et al., 2003; George et al., 2004; Bonazzi & Dumoulin, 2011).

- Of conventional drying systems, indirect drying produces higher product quality compared to hot air drying. This is because the flows into and out of the dryer are relatively small; when operating in a batch mode an indirect dryer is practically a closed system (Devahastin & Mujumdar, 2006).
- Vacuum drying and hot air drying methods (cabinet-air-through, fluid bed, pulsed fluid bed, and vibrated fluid bed dryers) give similar product quality (Grabowski et al., 2002; George et al., 2004).
- The product from the fluid bed drying compares satisfactorily with that from tray drying in terms of percent monoterpenes, percentage volatile oil and moisture content (Thomas & Varma, 1992).
- Combined drying methods like microwave combined spouted bed drying resulted in finished product with improved physical quality (color and rehydration) and nutritional quality (retention of total antioxidant activity - TAA) when compared hot air drying methods (Feng et al., 1999; George et al., 2004).
- Solar drying is less sensorially acceptable compared to hot air drying because its long drying time and low temperature encourage greater loss of color pigments and aroma compounds as well as browning reaction (Okilya et al., 2010; Leon et al., 2002).
- The color and aroma qualities of dried agricultural products using heat pump dryers are better than those using conventional hot air dryers (Schoenau et al., 1996). The retention of total chlorophyll content and ascorbic acid content is more in heat pump-dried samples with higher rehydration ratios and sensory scores compared to hot air dryer (Pal et al., 2008).

It is hard to compare the performance of different dryer types in term of final product quality without specifying the drying parameters and material characteristics. Although, a rough qualitative evaluation is assumed here in order to provide approximate data for the appraisal of quality performance in the rating and ranking of food drying technologies.

Table 4-6. Evaluation of the product quality of common food dryers

| ***Dryer type*** | ***Product quality*** |
|---|---|
| Contact cabinet dryer | L |
| Contact tunnel dryer | L |
| Plate dryer | M |
| Contact conveyor dryers | M |
| Rotary steam tube dryer | M |
| Drum dryer | M |
| Direct cabinet dryer | L |
| Direct tunnel dryer | L |
| Direct conveyor dryers | M |
| Chamber/bin dryer | L |
| Direct rotary dryer | M |
| Fluidized bed dryer | M |
| Spouted bed dryer | H |
| Spray dryer | H |
| Pneumatic flash dryer | H |
| Freeze dryer | VH |

#### 4.3.3.2 Fire and explosion hazards

The most common type of safety aspect associated to drying operation is fire and explosion. This risk is particularly due to three factors: process (material characteristic, operating conditions), engineering (plant layout, location, equipment), and management (risk assessment, housekeeping and maintenance) (Markowski & Mujumdar, 2006). In-depth analyses on the nature and evaluation of fire and explosion hazards in dryers have been reported by Abbott (1990), Gardiner (1997), Markowski and Mujumdar (2006), Chen (2008). Some important observations have been drawn from these studies:

- Fire and explosion hazards in indirect heating systems are reduced since there are no leaks in the barriers and deposit on the heat exchange surfaces. Drying medium is kept away from the combustible materials thanks to the well-insulated piping system.
- Direct heating systems present higher risk levels, therefore it is recommended not to use these for flammable materials.
- The fluctuations of feed rate and quality can lead to increased fire and explosion hazards. These fluctuations are most serious in the dryers where residence time of material is short, as in pneumatic conveyor dryer or spray dryer.
- The fire and explosion hazards are more severe in the dryers where the separation and collection of particles from the exhaust air must be done as an integral part of the operation as in pneumatic dryer, spray dryer, fluidized bed dryer or rotary dryer.
- Venting is one of the cheapest forms of protection. In the system where a part of exhaust air flow is recycled back to the drying process to improve thermal efficiency, fire ignition may arise from the penetration of fine, dry particles in the recirculated air into the hot zone of the dryer.
- Risk of fire and explosion hazards are eliminated when drying at low oxygen content as in a vacuum or a modified atmosphere (e.g., inserting with nitrogen).

From these observations, the risks of fire and explosion hazards of various dryer types have been assessed as in Table 4-7.

#### 4.3.3.3 Convenience of installation and operation

A comparison by Law and Mujumdar (2006) shows that dryers of fluid bed, conveyor and flash types demand maintenance at medium level while rotary dryers require quite higher maintenance. Additionally, control of a rotary dryer is more complicated than the others. This study also indicates that floor area must be large for installing a rotary dryer, flash dryer or conveyor dryer while a fluid bed dryer requires only a small space. Operating an indirect dryer in a continuous mode under vacuum is more complicated than the conventional drying operation.

Concerning the drying time, pneumatic is of the most rapid drying processes, followed by spray drying and drum drying. In most of the other types, the residence time of materials within the drying chamber is in the range of 10 - 60 minutes. Several batch systems as tray or tunnel dryers, solar dryers, freeze dryers even require up to 6 hours or more for a single run.

In Table 4-7, the evaluation of convenience of installation and operation of numerous dryer types are also introduced. It represents the compromise of different parameters during the installation phase (floor area) and operation phase (maintenance requirement, ease of control, drying time) of the drying equipment.

Table 4-7. Evaluation of the hazard and convenience aspects of some common food dryers

| *Dryer types* | *Fire and explosion hazards* | *Convenience of installation and operation* |
|---|---|---|
| Contact cabinet dryer | L | L |
| Contact tunnel dryer | L | L |
| Plate dryer | L | L |
| Contact conveyor dryers | L | M |
| Rotary steam tube dryer | M | H |
| Drum dryer | L | M |
| Direct cabinet dryer | M | L |
| Direct tunnel dryer | M | M |
| Direct conveyor dryers | M | M |
| Chamber/bin dryer | M | M |
| Direct rotary dryer | H | VH |

| *Dryer types* | *Fire and explosion hazards* | *Convenience of installation and operation* |
|---|---|---|
| Fluidized bed dryer | H | M |
| Spouted bed dryer | H | M |
| Spray dryer | VH | H |
| Pneumatic flash dryer | H | M |
| Freeze dryer | VL | H |

## 4.4 ENERGY PERFORMANCE

Four criteria are suggested for the appraisal of energy performance of the drying process: Specific thermal energy consumption, thermal efficiency, renewable energy ratio and energy recovery ratio. The specific thermal energy consumption is intended for evaluating the processing subsystem, the thermal efficiency is intended for both processing subsystem and heating subsystem, while renewable energy ratio and energy recovery ratio are respectively intended for heating and heat recovery subsystems.

### 4.4.1 Specific thermal energy consumption

Specific thermal energy consumption (STEC) is the ratio of thermal energy consumed per kg of water evaporated. In the practical situations, heat consumption in drying is determined by the measurement of heat transferred from the supplied hot air flow or the circulated steam flow. An alternative measure is based upon the analysis of energy balances. In the drying processes, the total heat supplied is spent on heating of material, water evaporation and heat losses. Considering the heat recovery in the drying process, the generic form of energy balance equation is presented as follows:

$$\sum \mathrm{Q_i} = \mathrm{Q_{He}} + \mathrm{Q_{Ev}} + \mathrm{Q_L} - \mathrm{Q_{Rec}} \qquad 4\text{-}1$$

Thermal energy consumption for heating of material, water vaporization and heat loss can be estimated from the parameters of feed and product (moisture content, temperature), engineering characteristics of the drying system (heating mode, processing mode…), operating conditions of the drying process (product throughput; temperature, humidity and flow rate of drying air; steam pressure…), amongst others. In this study, depend on the heating mode of the drying process, four mathematic models have been developed for the estimation of STEC, including models for hot air dryers, contact dryers, heat pump dryers and freeze dryers. These models are simplified as far as possible to reduce the data required to minimum necessary. Thus, heat losses are totally neglected in the models.

The criterion of STEC employs dynamic criteria approach that is calculated on the time-distributed basis (for batch drying) or space-distribute basis (for continuous drying). This approach allows one to easily compare the operation efficiencies of various dryers (Thankitsunthorn et al., 2005).

$$\mathrm{STEC} = \frac{\sum \mathrm{Q_i}}{\mathrm{m_w}} \qquad 4\text{-}2$$

From this we have the concept control volume (CV) which is kg of moisture removed per batch (kg/batch) in batch drying or kg of moisture removed per hour (kg/h) in continuous drying.

#### 4.4.1.1 Some balances and common relations:

1. Overall product mass, material mass and dry solid:

$$\mathrm{F_{mi}} = \mathrm{F_{md}} \times (1 + \mathrm{x_i}) \qquad 4\text{-}3$$

$$\mathrm{F_{mo}} = \mathrm{F_{md}} \times (1 + \mathrm{x_o}) \qquad 4\text{-}4$$

$$\mathrm{F_{mi}} = \mathrm{F_{mo}} \times \left(\frac{1 + \mathrm{x_i}}{1 + \mathrm{x_o}}\right) \qquad 4\text{-}5$$

2. Dry basis moisture content and wet basis moisture content of feed

$$\mathrm{x} = \frac{\mathrm{w}}{1 - \mathrm{w}} \qquad 4\text{-}6$$

3. Heat capacity of material and drying air

$$c_{mi} = c_w \times w_i + c_{md} \times (1 - w_i) \quad (4\text{-}7)$$

$$c_{mo} = c_w \times w_o + c_{md} \times (1 - w_o) \quad (4\text{-}8)$$

$$c_m = \frac{c_{mi} + c_{mo}}{2} \quad (4\text{-}9)$$

$$c_a = 1.005 + 1.88y_{ai} \quad (4\text{-}10)$$

Mass of moisture to be evaporated, material and dried product

$$m_w = F_{mi} - F_{mo} \quad (4\text{-}11)$$

**Calculating mass of feed material from evaporated water:**

$$m_w = F_{mo}\frac{1 - w_o}{1 - w_i} - F_{mo} = F_{mi} - F_{mi}\frac{1 - w_i}{1 - w_o} \quad (4\text{-}12)$$

4.4.1.2 Hot air drying

Hot air drying (convective or direct drying) accounts for over 90% of dehydrated food production (Mujumdar, 1997). In hot air drying system, heat is supplied by the heated air flow and evaporated moisture is carried away in the moving air. Heat transfer to the wet material is mainly by convection to the exposed surface of the material. The rate of water removal depends on the drying air conditions (high dry bulb temperature, low relative humidity and high velocity), the material and product properties and the dryer design. The STEC is usually estimated from heat supplied by the hot air flow. The drying process and psychrometric properties of the drying air are presented in Figure 4-19.

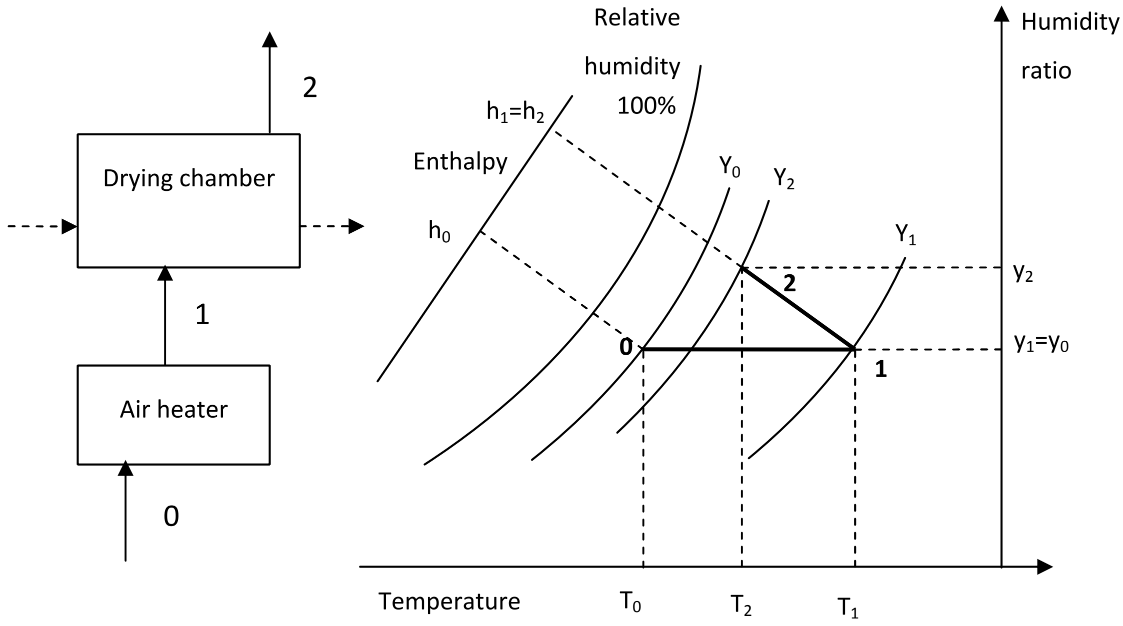


Figure 4-19. Schematic and psychrometric presentations of the hot air drying processes

Properties of the hot air at the states of the drying process are calculated using the equations as presented in Lụa (2006).

- State 0: ambient air

$$P_{s0} = P_{satm} = e^{\left(12 - \frac{4,026.42}{235.5 + T_{atm}}\right)} \tag{4-13}$$

$$y_0 = y_{atm} = 0.621 \frac{Y_{atm} \times P_{satm}}{P_{atm} - Y_{atm} \times P_{satm}} \tag{4-14}$$

$$h_{atm} = c_a \times T_{atm} + (\Delta H_{wv} + c_{wv} \times T_{atm}) \times y_{atm} \tag{4-15}$$

- State 1: inlet drying air

$$y_1 = y_0 \tag{4-16}$$

$$h_1 = c_a \times T_{a1} + (\Delta H_{wv} + c_{wv} \times T_{a1}) \times y_1 \tag{4-17}$$

$$P_{s1} = e^{\left(12 - \frac{4,026.42}{235.5 + T_{a1}}\right)} \tag{4-18}$$

- State 2: exhaust air or outlet drying air

The difference between the dry-bulb temperature of the exhaust air and its dew point should be at least 10°C in order to avoid the possibility of condensation in the downstream ductwork and air cleaning devices (Chen, 2008).

$$h_2 = h_1 \quad (4\text{-}19)$$

$$T_{a2} = T_{ao} = T_{dp2} + 10 \quad (4\text{-}20)$$

$T_{dp2}$ is obtained from the psychometric chart, extrapolated from the point of inlet drying air state (temperature $T_2$ and relative humidity $Y_2$) in an adiabatic process.

$$P_{s2} = e^{\left(12 - \frac{4{,}026.42}{235.5 + T_2}\right)} \quad (4\text{-}21)$$

$$y_2 = \frac{h_2 - c_a \times T_{a2}}{\Delta H_{wv} + c_v \times T_{a2}} \quad (4\text{-}22)$$

$$Y_2 = \frac{P_{atm} \times y_2}{P_{s2}(0.621 + y_2)} \quad (4\text{-}23)$$

Drying air mass flow rate:

$$F_a = \frac{m_w}{y_2 - y_0} \quad (4\text{-}24)$$

Thermal energy consumption for evaporation of the moisture to be removed

$$\sum Q_i = F_a(h_2 - h_0) \quad (4\text{-}25)$$

#### 4.4.1.3 Contact drying

In contact drying systems, material is dried by direct contact with the heated surface. Heat is transferred to the wet material by conduction from the surface through the bed of the wet solids. The temperature of heat transfer surfaces may range from -50°C (as in freeze drying) to about 300°C whereas the temperature of the solids in the dryer will be close to the boiling temperature of the moisture being evaporated at the dryer operating pressure. Only low gas flow or vacuum is needed to carry away the moisture evaporated from the wet material (Devahastin & Mujumdar, 2006).

Thermal energy supplied to the process is used for 2 different operations:

- Evaporating the water that leaves the materials

$$Q_1 = m_w \times \Delta H_{wv} \quad (4\text{-}26)$$

- Heating the material from its initial temperature, as it enters the dryer, to the drying temperature (boiling temperature of water in it at given dryer pressure):

$$Q_2 = F_w \times c_{wv}(T_D - T_{mi}) + F_{md} \times c_{md}(T_D - T_{mi}) \quad (4\text{-}27)$$

Total heat requirement

$$\sum Q_i = Q_1 + Q_2 \quad (4\text{-}28)$$

#### 4.4.1.4 Heat pump drying

Recently, there has been a great interest in using heat pump assisted dryers for drying of food products. A heat pump drying system consists of two different components: the heat pump system and the drying chamber. Drying takes place in a closed cycle as shown in Figure 4-20. Drying air is passed through the drying chamber and pick up the moisture from the product to be dried. The humid air exits the dryer is then discharged to the evaporator where the moisture is cooled down and condensed. Latent heat of condensation is absorbed by the evaporator for boiling the refrigerant. The refrigerant in the evaporator undergoes a 2-phase-change from liquid to vapor. The refrigerant vapor is then compressed and becomes superheated at high pressure at the compressor. The cooled and dry air absorbs the heat from the superheated refrigerant at the condenser for the new drying cycle.

More details of the heat pump dryer types and the description of the drying cycle can be largely found in Kiang and Jon (2006), Colak and Hepbasli (2009), Jangam and Mujumdar (2012), Patel and Kar (2012).

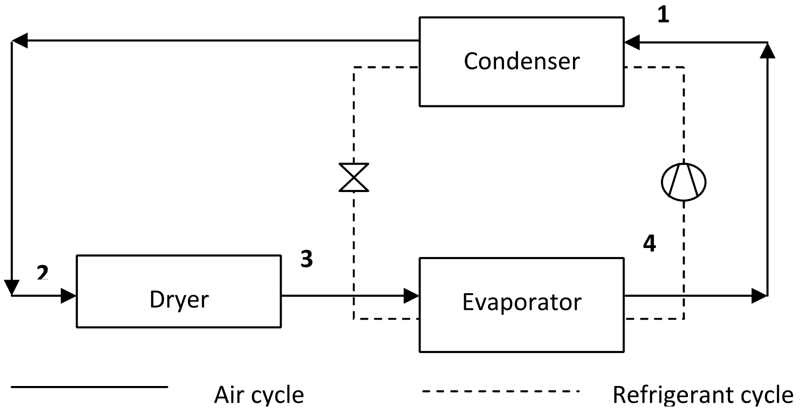


Figure 4-20. Schematic presentation of a heat pump drying system (adapted from Kiang & Jon, 2006)

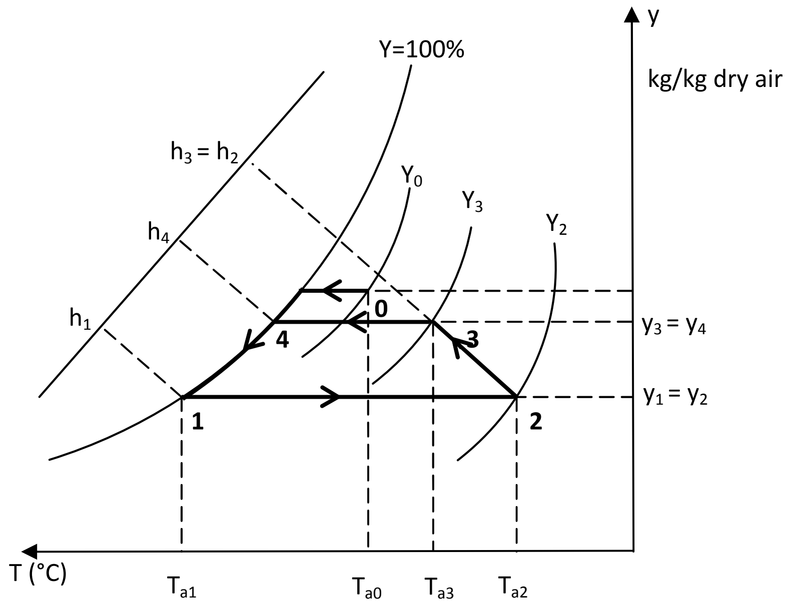


Figure 4-21. Air cycle of heat pump drying process on psychometric chart

**Note:**

State 0: ambient air

State 1: cold and humidified air comes out from the evaporator

State 2: drying air comes out of the condenser

State 3: drying air comes out of the drying chamber

State 4: drying air inside the evaporator

Path 1-2: process of air heating at constant humidity ratio in the condenser

Path 2-3: drying process

Path 3-4-1: air cooling and condensing process in the evaporator

The properties of drying air at the states of the process (Lụa, 2006):

- State 1:

$$Y_1 = 100\% \tag{4-29}$$

$$P_{s1} = e^{\left(12 - \frac{4,026.42}{235.5 + T_{a1}}\right)} \tag{4-30}$$

$$y_1 = 0.621 \frac{Y_1 \times P_{s1}}{P_{atm} - Y_1 \times P_{s1}} \tag{4-31}$$

$$h_{a1} = c_a \times T_{a1} + (\Delta H_{wv} + c_{wv} \times T_{a1}) \times y_1 \tag{4-32}$$

- State 2:

$$y_2 = y_1 \tag{4-33}$$

$$h_{a2} = c_a \times T_{a2} + (\Delta H_{wv} + c_{wv} \times T_{a2}) \times y_2 \tag{4-34}$$

- State 3:

$$h_{a3} = h_{a2} \tag{4-35}$$

$$y_3 = \frac{h_{a3} - c_a \times T_{a3}}{\Delta H_{wv} + c_{wv} \times T_{a3}} \tag{4-36}$$

Drying air mass flow rate

$$F_a = \frac{m_w}{y_3 - y_2} \tag{4-37}$$

Thermal energy consumption for the evaporation of the moisture to be removed

$$\sum Q_i = F_a(h_3 - h_1) \tag{4-38}$$

#### 4.4.1.5 Freeze drying

Freeze drying is a special case of contact drying. In the freeze drying plant, three process sections are especially energy consuming (Liapis & Bruttini, 2006). Section 1 involves the freezing of the wet product. Section 2 involves the controlled supply of heat to the product to cover requirements for the sublimation and desorption processes (primary and secondary drying stages). Section 3 involves the removal from the freeze drying chamber of the vast volumes of water vapor released during the sublimation and desorption processes. Of these three process sections, removal of the water vapor always consumes the largest amount of energy.

Figure 4-22 summarizes the procedure of the freeze drying and the energy utilization in the process.

For calculating energy consumption of the freeze drying process, some assumptions are made as follows:

- All the water contained in the feed material mass (including bounded and unbounded water) is completely transformed into the frozen state.
- 100% of the water to be removed is dried in the first drying state (by sublimation), thus $Q_3 = 0$.

Energy is supplied to freeze drying process under 2 types: energy for freezing and energy for heating.

**Energy for freezing:**

1. Heat extract for cooling and freezing of material includes:
    - Heat extracted from lowering the material from initial temperature to freezing temperature of water in it
    - Heat extracted from freezing the water content in the feed material
    - Heat extracted from lowering the frozen water and dry basis to the freeze-drying temperature

$$Q_1 = [F_{md} \times c_{md}(T_{mi} - T_{wf}) + m_w \times c_w(T_{mi} - T_{wf})] + F_w \times \Delta H_{wF} + [F_{md} \times c_{md}(T_{wf} - T_{FD}) + F_w \times c_{wf}(T_{wf} - T_{FD})] \quad (4\text{-}39)$$

2. Heat removed by ice condensation of vapor water in the chamber

$$Q_4 = m_w \times \Delta H_{wC} \quad (4\text{-}40)$$

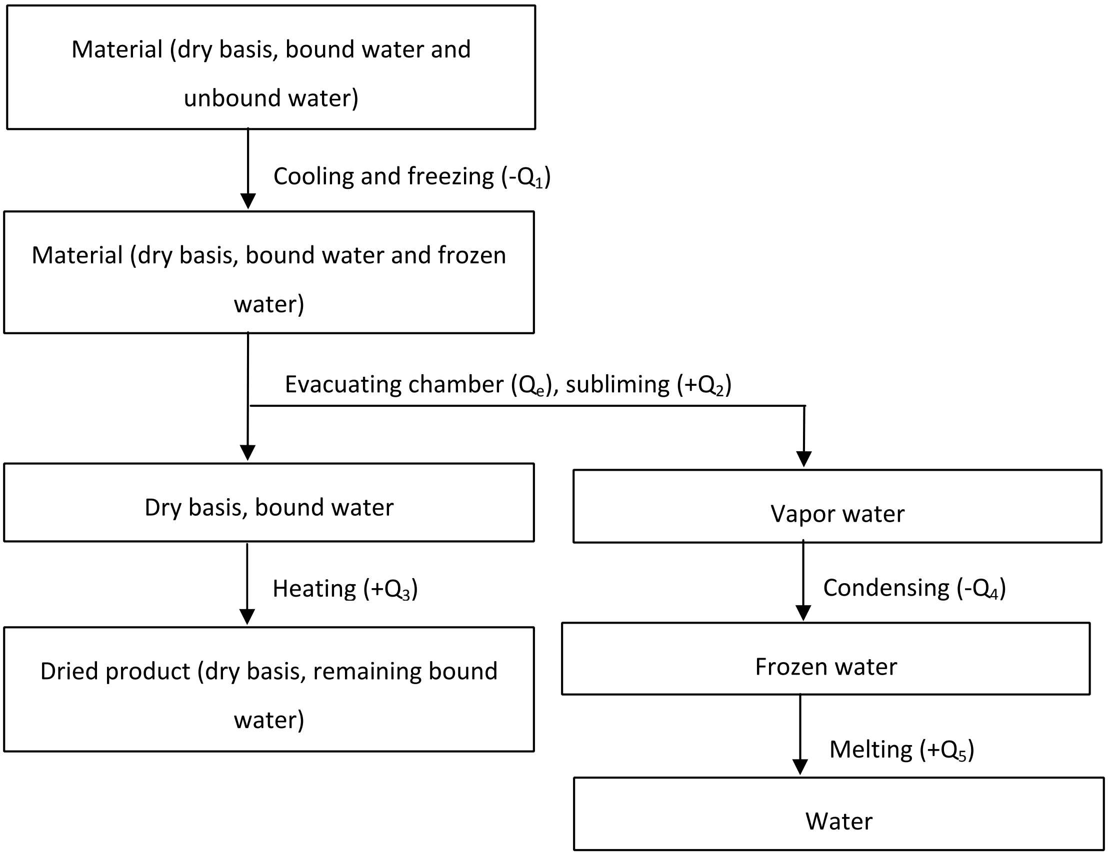


Figure 4-22. Energy utilization in the freeze drying process

**Energy for heating:**

1. Heat required to sublime the ice water at freeze drying temperature

$$Q_2 = m_w \times \Delta H_{wS} \quad (4\text{-}41)$$

2. Heat require to melt the ice collected at the condenser after the completion of the drying cycle

$$Q_5 = m_w \times c_{wf}(0 - T_{FD}) + m_w \times \Delta H_{wM} \quad (4\text{-}42)$$

**Total energy consumption**

$$\sum Q_i = |Q_1| + Q_2 + Q_3 + |Q_4| + Q_5 \qquad 4\text{-}43$$

4.4.1.6 Drying process specification

A majority of dryers in the food industry are of the hot air type. Here, data necessary for the estimation of thermal energy consumption of various hot air dryers have been collected, analyzed and stored in the database. The drying conditions should be determined so that desired moisture content can be obtained without any adverse effect on the product quality.

In hot air dryers, the most important factor is drying air temperature. Increase of drying air temperature leads to decrease of energy consumption, however product deterioration may occur.

For highest efficiency, drying of same solids at different dryer types subjects to variation in drying conditions. In conventional drying systems like tray dryers, tunnel dryers, belt dryers, drying takes place quite slowly due to the low contacting efficiency between the drying medium and material. Hence, the drying temperature should be set quite lower than the maximum temperature to which the substance can be exposed without any quality deterioration. In the more advanced drying systems like spray, pneumatic and drum dryers, the retention time of a few seconds permit drying heat sensitive material at higher temperature. The rapid evaporation rate allows high drying air temperature can be applied without affecting the product. The range of product temperature and resident time of common food drying systems are shown in Figure 4-23.

Information of appropriate drying conditions of food products in various dryer types are dispersedly available in forms of experimental studies, modeling or simulation studies. Annex 4-2 summarizes the parameters for drying of foods that have been monitored in many hot air systems.

Within the scope of this study, in order to facilitate the calculation of STEC, food dryers have been categorized into 3 groups according to the drying speed that is specified by the drying temperature and the residence time of material in the drying chamber.

In the first group, drying of food is recommended to take place at low temperature. In such systems, the low contacting efficiency between the drying medium and material requires drying temperature to be set much lower than the maximum allowable temperature of material. During the drying process, the material stays stable in the support tray or band, drying takes place quite slowly, up to 60 minutes or more. Drying temperature of many fruit pulps in such systems is advisably limited to 60 - 85°C, and the temperature of drying air is generally 20 - 25°C higher than that of the material (Barta, 2006). Solar dryers, cabinet tray dryers, tunnel dryers, conveyor dryers are tentatively assigned to this group.

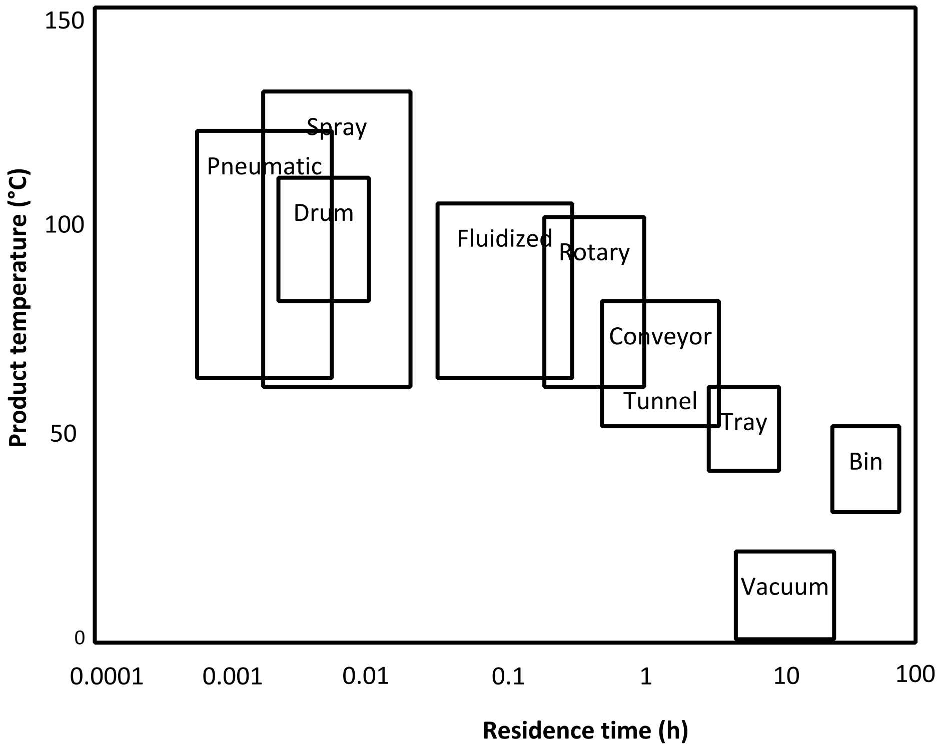


Figure 4-23. Drying conditions of common food dryers

In the second group, the rate of heat transfer is significantly increased thanks to the good solid mixing effect given by fluidized bed, spouted bed and other mechanical operations. This in turn leads to higher rate of moisture removal in comparison to the more traditional drying systems. In doing so, the outlet product temperature for many food products is normally in thermal equilibrium with the outlet air temperature due to the high transfer rate of heat between the air and the material bed. Drying time from 1 minute up to 2 hours may occur. Fluidized bed dryers, spouted bed dryers, rotary dryers are classified into this group.

In the third group, the large surface area for heat and mass transfer and the high heat and mass transfer coefficients result in high drying rates and consequently, high drying capacity (Borde & Levy, 2006). One of the features of these types of dryers is the relatively short contact time between the drying medium and the particulate materials (0.5 - 10s) at the drying section. Because of this, although operating gas temperature for many food products is normally rather high (in the range of 150 - 180°C), the material temperature stays always low in the drying process. Such systems are spray dryers, and pneumatic dryers.

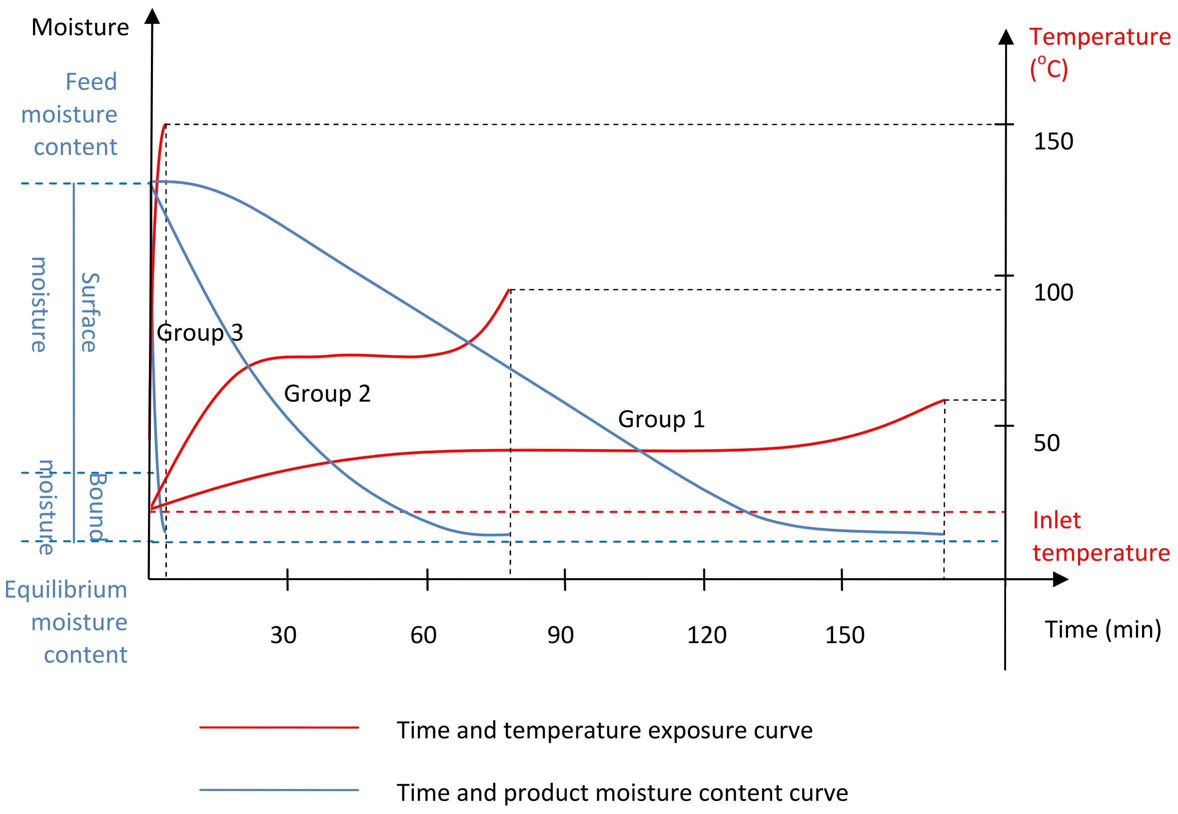


Figure 4-24. Typical drying curves for the three groups of drying technologies

Contact dryers are likewise categorized into 3 groups. The first group involves dryer types in which drying process takes place at low temperature like tray dryers, tunnel dryers and conveyor dryers. Contact rotary dryers for instances steam tube dryers, rotating batch vacuum dryers, agitated dryers are classified into the second group. The third group consists of drum dryers. Freeze dryers and heat pump dryers are special cases that use electric for the particular water removal processes. Due to the specific calculations of energy requirement, they are documented as the standalone processes. Figure 4-24 illustrates the typical drying curves of the aforementioned groups.

From this viewpoint, data of drying conditions necessary for the calculations of STEC has been compiled correspondingly. The values of hot air temperature, relative humidity, specific heat capacity and so on are compiled with TFNs in the database to address the range of the possible values.

Table 4-8. Grouping of food drying technologies

| ***Group*** | ***Dryer type*** | | ***Description*** |
|---|---|---|---|
| | **Hot air dryer** | **Contact dryer** | |
| Group 1 - Drying at low speed | Solar dryer, direct tray dryer, tunnel dryer, conveyor dryer | Contact tray dryer, tunnel dryer, conveyor dryer | Low contacting efficiency of solid and drying medium<br>Material stays stable in the support tray or band<br>Drying process takes place quite slowly, up to 60 min or more<br>Drying takes place at low temperature, much lower than the maximum allowable temperature of material |
| Group 2 - Drying at moderate speed | Rotary dryer, fluidized bed dryer, spouted bed dryer | Rotary dryer, agitated dryer | Good mixing effect increase the rate of heat transfer between the heating medium and the material bed and the higher rate of moisture removal<br>The outlet product temperature is in thermal equilibrium with the outlet air temperature |
| Group 3 - Drying at high speed | Pneumatic/flash dryers, spray dryer | Drum dryer | The large surface area for heat and mass transfer and high convective heat and mass transfer coefficients lead to high drying rates and high drying capacity<br>Relatively short contact time between the drying medium and particulate materials<br>Although operating gas temperature is normally rather high (150 - 180°C), the material temperature stays always low in the drying process |

### 4.4.2 Thermal efficiency

Thermal efficiency is the most common indicator used in the performance evaluation of industrial dryers. In this study, thermal efficiency is used in evaluating two subsystems: processing subsystem and heating subsystem.

**Drying efficiency**

Thermal efficiency of the processing subsystem (namely drying efficiency) concerns the effectiveness of moisture removal by the drying mediums. It is principally calculated by following equation:

$$\textit{Drying efficiency} = \frac{\textit{Thermal energy used for removal of water}}{\textit{Thermal energy supplied by heating medium}}$$

The data of drying efficiency of various technologies has been compiled in the database using the data taken from various literature sources as shown in Table 4-9.

Table 4-9. Drying efficiency of various food dryers

| ***Technology*** | ***Drying efficiency (%)*** | ***Reference*** |
|---|---|---|
| Contact cabinet dryer | 50 - 80 | Crapiste and Rotstein (1997) |
| Contact tunnel dryer | 35 - 60 | Crapiste and Rotstein (1997) |
| Plate dryer | 50 - 80 | Crapiste and Rotstein (1997) |
| Contact conveyor dryers | 35 - 60 | Crapiste and Rotstein (1997) |
| Rotary steam tube dryer | 75 - 90 | Strumillo et al. (2006), Crapiste and Rotstein (1997) |
| Drum dryer | 70 - 85 | Crapiste and Rotstein (1997) |
| Direct cabinet dryer | 50 - 80 | Crapiste and Rotstein (1997), Soysal and Oztekin (2001), Akpina (2007) |
| Direct tunnel dryer | 35 - 40 | Strumillo et al. (2006), Crapiste and Rotstein (1997) |
| Direct conveyor dryers | 35 - 60 | Crapiste and Rotstein (1997) |

| *Technology* | *Drying efficiency (%)* | *Reference* |
|---|---|---|
| Chamber/bin dryer (solar dryer) | 20 - 25 | Mohanraj and Chandrasekar (2008), Kothari et al. (2009), Slama and Combarnous (2011) |
| Direct rotary dryer | 40 - 70 | Strumillo et al. (2006), Crapiste and Rotstein (1997), Iguaz et al. (2003, 2002) |
| Fluidized bed dryer | 40 - 80 | Strumillo et al. (2006), Crapiste and Rotstein (1997) |
| Spouted bed dryer | 40 - 80 | Strumillo et al. (2006), Crapiste and Rotstein (1997) |
| Spray dryer | 50 - 60 | Strumillo et al. (2006), Crapiste and Rotstein (1997) |
| Pneumatic flash dryer | 50 - 75 | Strumillo et al. (2006), Crapiste and Rotstein (1997), Prvulovic et al. (2007, 2009), Tolmač (1997) |
| Freeze dryer | 10 - 20 | Grabowski et al. (2002) |

**Heat supply efficiency**

Thermal efficiency of the heating subsystem concerns the efficiency of the conversion of the primary energy sources (for i.e. fossil fuel, biomass, and solar energy) to the secondary energy types that are used directly in the drying process (for i.e. steam, hot air, hot water).

A huge amount of data has been reported in the literature about the thermal efficiency of the energy conversion processes. In Table 4-10, the values of thermal efficiency of the technologies under study are displayed.

Table 4-10. Thermal efficiency of the heat supply technologies

| *Technology* | *Thermal efficiency (%)* | *Reference* |
|---|---|---|
| Boiler/heater-non renewable energy | 70 – 85 | Adapted from Benetle (2002), Canada Mortage and Housing Corporation (2008) |
| Boiler-renewable energy | 70 – 75 | Adapted from Benetle (2002), Canada Mortage and Housing Corporation (2008) |

| *Technology* | *Thermal efficiency (%)* | *Reference* |
|---|---|---|
| Boiler-mixed type | 70 – 80 | Adapted from Benetle (2002), Canada Mortage and Housing Corporation (2008) |
| Solar collector | 40 – 60 | Leon et al. (2002), Bala et al. (2009), Slama and Combarnous (2011) |
| Heat pump | 90 – 100 | Perera and Rahma (1997) |
| Refrigeration plant | 10 – 20 | Grabowski et al. (2002) |

### 4.4.3 Energy recovery ratio

There is a number of heat recovery options available for the drying process. Heat recirculation and heat exchange are the two most common and simplistic methods. Recuperation of waste heat contained in the outlet drying air and transferring it into inlet drying air is strongly recommended because it limits the amount of heat released to the environment (Grabowski & Boye, 2012). Studies claimed that hot air recirculation can achieve up to 50% of energy savings in convective drying of bio product. The more heat is recirculated, the more energy is saved. However increase of exhaust air recirculation fraction can cause the increase of drying time and decrease of drying capacity and final product quality (Pelegrina et al., 1999). Table 4-11 presents the literature data of exhaust air recirculation fraction and corresponding energy savings.

Table 4-11. Review of studies on heat recovery in the drying process

| *Dryer type* | *Product* | *Type of heat recovery* | *Air recuperation ratio* | *Energy saving ratio* | *Reference* |
|---|---|---|---|---|---|
| Concurrent rotary dryer | Hay | Exhaust air recirculation | 30% | 17 - 27% | Schoenau et al. (1996) |
| Batch type dryer | Peanut | Exhaust air recirculation | - | 26% | Young (1984) |
| Tunnel dryer | Fruit | Exhaust air | partly | 15% | Thompson et al. |

| ***Dryer type*** | ***Product*** | ***Type of heat recovery*** | ***Air recuperation ratio*** | ***Energy saving ratio*** | ***Reference*** |
|---|---|---|---|---|---|
| | | recirculation | | | (1981) |
| Rotary dryer | Vegetable and fruit | Exhaust air recirculation | 80 - 95% | 21 - 38.54% | Iguaz et al. (2002) |
| Tunnel dryer | Grape | Exhaust air recirculation | 92 - 99% | - | Vagenas and Marinos-Kouris (1991) |
| Cabinet dryer | Peeled longan | Exhaust air recirculation | 70 - 90% | 42% | Tippayawong etal. (2009) |
| - | Apple, peach | Exhaust air recirculation | 70 - 80% | 46 - 50% | Liu (1995) |
| Spray dryer | - | Air to air heat exchanger | - | 18% | Gea Niro (2012) |
| Spray dryer | Milk | Air to air heat exchanger | - | 10 - 30% | Reay (2008) |
| Concurrent counterflow dryer | Grain | Heat pipe exchanger | - | 10 - 18% | Sokhansanj and Bakker-Arkema (1981) |
| Fixed bed dryer | Grain | Heat pipe exchanger | - | 10% | Lai and Foster (1977) |

Heat exchangers, on the other hand, can be used in either continuous or batch type high-temperature dryers. Exchange of waste heat from exhaust air is a good alternative for processes where mingling of exhaust air and inlet air is not allowed. Heat exchangers allow for higher drying capacity but unfortunately require higher investment cost.

In this study, performance of drying system with respect to energy recovery is evaluated by heat recovery ratio. Heat recovery ratio of the system with exhaust air recirculation and exhaust air heat exchanger are calculated as follows.

Heat recovered from exhaust air flow:

- Exhaust air recirculation:

$$Q_{Rec} = r \times F_a(T_{ao} - T_{atm}) \quad \text{4-44}$$

- Exhaust air heat exchanger: (assume that enthalpy efficiency of heat exchanger is in between 60 - 80% as mostly recommended by the equipment suppliers)

$$Q_{Rec} = \mu_{hex} \times F_a(T_{ao} - T_{atm}) \quad \text{4-45}$$

Heat recovery ratio is the ratio of the recovered energy in the exhaust air and the total energy consumption of the drying process.

$$R_{Rec} = \frac{Q_{Rec}}{\sum Q_i} \quad \text{4-46}$$

### 4.4.4 Renewable energy utilization

Utilization of renewable energy has been especially promoted worldwide to face the challenges of resource depletion and climate change. For this reason, in this study, the utilization of solar energy or biomass fuel in the drying process is highly encouraged by using the criterion of renewable energy utilization ratio ($R_{Renew}$). $R_{Renew}$ denotes the ratio of renewable energy consumption ($Q_{Renew}$) and the total heat consumption for the process ($\sum Q_i$) and is calculated in Equation 4-47.

$$R_{Renew} = \frac{Q_{Renew}}{\sum Q_i} \quad \text{4-47}$$

## 4.5 CHAPTER FINDINGS

The proposed decision support framework has been successfully tested for the drying process in the development of a decision support system for food dryer selection. Performances of the drying systems with respect to environmental, economic and social sustainability are comprehensively considered in the selection process. This DSS is correspondingly expected more reliable than the existing developments in this field.

Facing the complexity and diversity of the drying process, the DSS is developed to be comprehensive, yet simple enough for being used by the non-technical person.

The core components of this DSS are the database of drying technologies and food products and the database of dryer's performance with respect to the energy, economic and social criteria. A huge amount of data has been carefully screened in order to make the databases as exhaustive and consistent as possible.

A variety of food drying technologies has been collected and profiled in the database so far. Nevertheless, a limited number of special or emerging technologies is not yet included in the database, for example dielectric drying, infrared drying, combined drying, and super heated-steam drying. The reason is that they are not commonly found in the practice of food industry, and that the selection of such technologies demands great time and effort which go beyond the confines of this study.

The energy performance with respect to specific thermal energy consumption is reasonably estimated using the calculation models that are particularly developed in this study. The performances with respect to other criteria, especially the economic criteria, are currently qualitatively evaluated that may be underestimated in the overall final decision. It is, however, acceptable due to the fact that there would be a huge amount of data to be recorded and that such data could be unavailable or unobtainable within the scope of this study.

During the testing of the DSS, it has been found that the rank of a set of alternatives can change if a new criterion is introduced into the set of criteria. For this reason, it is strongly recommended to have a consistent and comprehensive criteria system in order to ensure the accuracy of the results.

The system is currently working well on MS-Excel. The programming of the DSS on MS-Excel requires less computational efforts. However, it is obviously more troublesome and annoying while working with it on Excel. Therefore a more professional software platform is desirable for future applications.

# 5. CASE STUDIES

This section demonstrates the application of the proposed decision support system for the selection of food drying technologies in two case studies: drying of granular coconut and drying of cassava starch. The two applications have been carried out for both case studies: selection of new facilities and selection for changing the used technologies of the existing facilities.

In the case of selecting drying technologies for new facilities, most of the data necessary for the selection process can be retrieved from the database. The DSS works in likely a non-interactive mode and results in list of drying technologies for a food product under consideration.

In the case of changing the used technologies of the existing facilities, the information concerning the thermodynamic properties of the existing drying system is required. The energy performance of the existing drying process, namely the base-case alternative, with respect to specific thermal energy consumption, thermal efficiency, renewable energy ratio and energy recovery ratio will be calculated. Ratings and rankings of other drying technologies will be defined on the basis of the performance of the existing technology. The DSS therefore results in the technologies which are more preferable in terms of sustainability rather than the base-case technology.

Several food processing companies in Vietnam were chosen for the base-case alternatives in the application of changing the used technologies. Vietnam is an agro-based country, the food sector accounts for more than 18% of the total industrial production value[4]. The drying process in the food industry, on the other hand, still challenges the old-fashioned and backward situation. Examining the case studies for Vietnam condition is therefore very meaningful and might foster the trend of technology transition toward sustainability.

[4] Data for 2009, taken from the website of the General Statistics Office of Vietnam (http://www.gso.gov.vn/default.aspx?tabid=391&idmid=3&ItemID=11926, accessed on May 15, 2012)

## 5.1 DRYING OF FOODS IN VIETNAM

Food industry is one of the major industrial sectors in Vietnam. In 2008, there were 6.980 food and beverage manufacturing enterprises, and the number of employees in the food sector amounted to 463.913 people, accounts for 18.2% and 12.3% respectively of those of the entire manufacturing sector[5].

Food industry in Vietnam is principally an agriculture-based sector and drying plays a significant role in numerous food manufacturing processes. Also, the drying equipment used in most enterprises is quite traditional or with little modification, except in some recently built plants.

A large number of food processing enterprises is at small and medium scale. Sun and hand-operated drying are therefore the most common technologies for post harvest preservation of agricultural and seafood products. Weather-dependency, low product quality and air pollution usually challenge the sun drying process, while the labor, energy and production cost and non-uniform product quality usually challenge the hand-operated drying process.

The local, custom-built drying equipment has been largely accepted, especially with rice dryers. However, the development and utilization of advanced drying technologies are still limited.

Renewable energy sources including biomass fuel (for instance straw, rice husk, firewood) and solar energy are largely available in the area. For this reason, drying technologies using renewable energy sources have been developed extensively in Vietnam.

Of the above two case studies, desiccated coconut is mainly produced in the Mekong Delta provinces such as Ben Tre, Tra Vinh, Vinh Long, and exported to the Middle East, China, and European countries. The production of desiccated coconut in Vietnam has a history of more than 30 years. However, most of the desiccated coconut processing enterprises in Vietnam are at small scale, in lack of capital and an efficient quality management system. Before, coconut was usually dried in tray dryers, causing product with non-uniform quality and bacterial

[5] Data taken from the website of the Ministry of Industry and Trade - Socialist Republic of Vietnam (http://tttm.vecita.gov.vn/dstk.aspx?NewID=183E&CateID=93, accessed on May 15, 2012)

contamination. Conveyor, fluid bed and rotary dryers have become the common technologies at present.

Cassava is one of the most important food sources for human alimentation. It is also a source of commercial animal feed, and a material for the food, candy, alcohol, noodle, paper, and textile industries. Cassava in Vietnam is among the four most important food crops and plays an important role in the national food security. Vietnam is the third largest cassava starch export country in the world, after Indonesia and Thailand (CPI & VNCPC, 2008). At industrial production scale, cassava starch drying technologies exist in the types of drum dryers, spray dryers for liquid or paste materials; and flash/pneumatic dryers and cabinet dryers for granular materials.

## 5.2 SELECTION OF COCONUT DRYERS

Desiccated coconut is one of the important materials in the manufacture of many bakery products. Desiccated coconuts are graded by its size into fine and medium grades. The value of desiccated coconut lies at the fat content that is categorized into full fat (minimum of 60% fat) or reduced fat (lesser than 60% fat). Other specifications of desiccated coconut product are shown in Table 5-1.

Table 5-1. General specification of desiccated coconut

| ***Attribute*** | ***Value*** |
|---|---|
| Color | Natural White, free from rancidity, musty or objectionable odor. |
| Flavor | Mild and sweet coconut taste with no off-flavor |
| Impurity | Not more than 5 dark specks per 100 gram |
| Moisture content (% maximum) | 3 |
| Fat content (%) | 65 ± 3 |
| Free fatty acid (% maximum) | 0.3 |

| *Attribute* | *Value* |
|---|---|
| pH | 6.1 - 6.8 |
| *E. coli* | Negative |
| *Salmonella* | Negative |

In general, the production process of desiccated coconut involves several steps as follows:

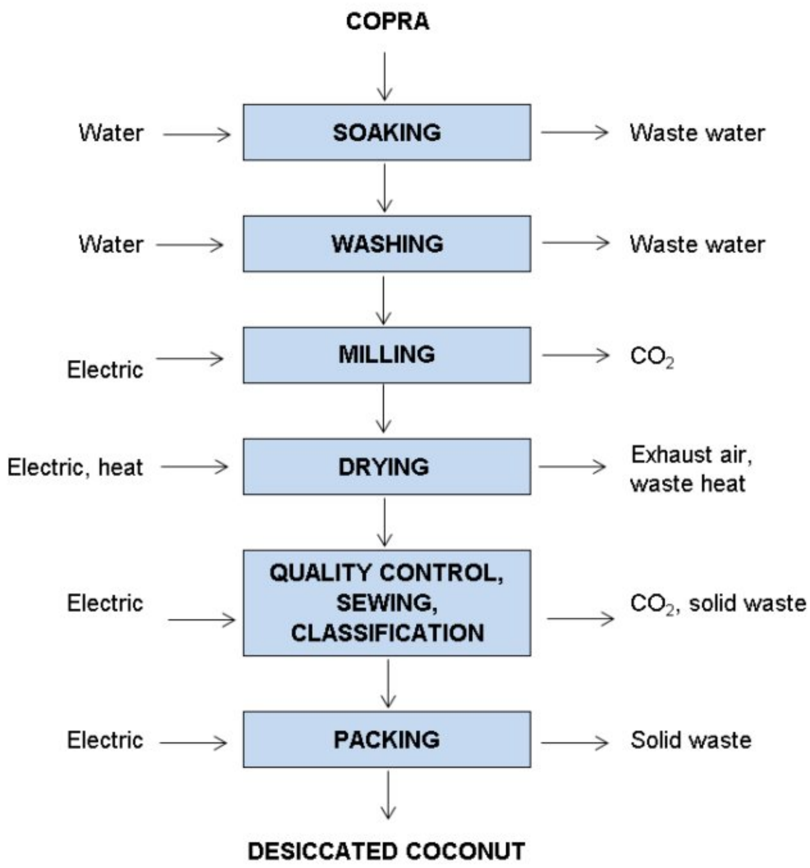


Figure 5-1. General production process of desiccated coconut

In the processing of desiccated coconut product, drying is the most energy-intensive operation. It accounts for 60% of the total energy consumption of the process. Coconut dryers appear in diverse types, including tray dryers, conveyor dryers, fluid bed dryers, rotary dryers, flash dryers, and others, among which the fluid bed drying has been found technology of greatest interest.

### 5.2.1 Selection of new facility

**Preliminary selection step**

In the preliminary selection step, desiccated coconut is characterized as follows in the database:

| | |
|---|---|
| Name: | **Desiccated coconut** |
| Product ID: | **DA15.332.6** |
| Physical form of feed: | **Large pieces, flakes and extrudates** |
| Nature of wet feed: | **Free flowing, non-cohesive, loose** |
| Special requirements of product: | **Uncontaminated** |
| Allowable drying temperature: | **Bellow boiling temperature** |
| | **Above boiling temperature** |
| | **Below freezing temperature** |
| Product throughput: | **Medium** |
| Mode of upstream and downstream operations: | **Continuous** |

Figure 5-2. Specification of desiccated coconut for the preliminary selection

The specifications regarding "product throughput" and "mode of upstream and downstream operation" are user-defined. Drying technologies appropriate for the process are accordingly suggested. In the preliminary selection step, there are 7 processing technologies, 5 heating technologies and 3 heat recovery technologies proposed for the product. The subsystem technologies recommended by the DSS are shown in Figure 5-3.

| PROCESSING SUBSYSTEM | | | HEATING SUBSYSTEM | | | HEAT RECOVERY SUBSYSTEM | | |
|---|---|---|---|---|---|---|---|---|
| **No.** | **ID** | **Technology** | **No.** | **ID** | **Technology** | **No.** | **ID** | **Technology** |
| 1 | PS02 | Contact tunnel dryer | 1 | HS01 | Boiler/heater-non renewable e | 1 | RS01 | No heat recovery |
| 2 | PS04 | Contact conveyor dryers | 2 | HS02 | Boiler-renewable energy | 2 | RS02 | Exhaust air recirculation |
| 3 | PS05 | Rotary steam tube dryer | 3 | HS03 | Boiler-mixed type | 3 | RS03 | Exhaust air heat exchanger |
| 4 | PS08 | Direct tunnel dryer | 4 | HS04 | Solar collector | | | |
| 5 | PS09 | Direct conveyor dryers | 5 | HS05 | Heat pump | | | |
| 6 | PS11 | Direct rotary dryer | | | | | | |
| 7 | PS12 | Fluidized bed dryer | | | | | | |

Figure 5-3. Pre-selected subsystem technologies for drying of coconut

These subsystem technologies constitute of 51 technologies of the overall system as partly listed in Figure 5-4.

| | SYSTEM | | SUBSYSTEM | | |
|---|---|---|---|---|---|
| **No.** | **ID** | **Technology** | **PS** | **HS** | **RS** |
| 1 | A019 | Contact tunnel dryer - Boiler/heater-non renewable energy - No heat recovery | PS02 | HS01 | RS01 |
| 2 | A022 | Contact tunnel dryer - Boiler-renewable energy - No heat recovery | PS02 | HS02 | RS01 |
| 3 | A025 | Contact tunnel dryer - Boiler-mixed type - No heat recovery | PS02 | HS03 | RS01 |
| 4 | A055 | Contact conveyor dryers - Boiler/heater-non renewable energy - No heat recovery | PS04 | HS01 | RS01 |
| 5 | A058 | Contact conveyor dryers - Boiler-renewable energy - No heat recovery | PS04 | HS02 | RS01 |
| 6 | A061 | Contact conveyor dryers - Boiler-mixed type - No heat recovery | PS04 | HS03 | RS01 |
| 7 | A073 | Rotary steam tube dryer - Boiler/heater-non renewable energy - No heat recovery | PS05 | HS01 | RS01 |
| 8 | A076 | Rotary steam tube dryer - Boiler-renewable energy - No heat recovery | PS05 | HS02 | RS01 |
| 9 | A079 | Rotary steam tube dryer - Boiler-mixed type - No heat recovery | PS05 | HS03 | RS01 |
| 10 | A127 | Direct tunnel dryer - Boiler/heater-non renewable energy - No heat recovery | PS08 | HS01 | RS01 |

Figure 5-4. Pre-selected system technologies for drying of coconut

**Final selection step**

The subsystem technologies have been taken into the rating and ranking process in the final selection step. Selecting the new facility, the aggregated normalization method is used to define the ratings and rankings of the technology alternatives.

The justification data of the subsystem technology alternatives with respect to energy, economic and social performances is retrieved from the database as in Figure 5-5. Here, the data of STEC of the processing technologies (criteria C11 in Figure 5-5) is calculated with the models as presented in Section 4.4.1, using the data retrieved from the database as detailed in Annex 4-1. The ratings and rankings of the subsystem technologies are step-by-step computed; the intermediate results are viewed in the spreadsheets from Annex 4-2 to Annex 4-5.

| PROCESSING SUBSYSTEM | | SUB-CRITERIA | | | | | | |
|---|---|---|---|---|---|---|---|---|
| ID | Technology | $C_{11}$ | $C_{12}$ | $C_{21}$ | $C_{22}$ | $C_{31}$ | $C_{32}$ | $C_{33}$ |
| PS02 | Contact tunnel dryer | (2465.4 , 2508.67 , 2556.05) | (35 , 47.5 , 60) | (0.33 , 1 , 3) | (0.2 , 0.33 , 1) | (0.2 , 0.33 , 1) | (0.2 , 0.33 , 1) | (0.2 , 0.33 , 1) |
| PS04 | Contact conveyor dryers | (2465.4 , 2508.67 , 2556.05) | (35 , 47.5 , 60) | (0.33 , 1 , 3) | (0.33 , 1 , 3) | (0.33 , 1 , 3) | (0.2 , 0.33 , 1) | (0.33 , 1 , 3) |
| PS05 | Rotary steam tube dryer | (2401.7 , 2478.92 , 2560.25) | (75 , 82.5 , 90) | (1 , 3 , 5) | (1 , 3 , 5) | (0.33 , 1 , 3) | (0.33 , 1 , 3) | (1 , 3 , 5) |
| PS08 | Direct tunnel dryer | (1117.08 , 3116.91 , 6849.63) | (35 , 37.5 , 40) | (0.2 , 0.33 , 1) | (0.2 , 0.33 , 1) | (0.2 , 0.33 , 1) | (0.33 , 1 , 3) | (0.33 , 1 , 3) |
| PS09 | Direct conveyor dryers | (1117.08 , 3116.91 , 6849.63) | (35 , 47.5 , 60) | (0.2 , 0.33 , 1) | (0.33 , 1 , 3) | (0.33 , 1 , 3) | (0.33 , 1 , 3) | (0.33 , 1 , 3) |
| PS11 | Direct rotary dryer | (1603.23 , 3178.27 , 5423.7) | (40 , 55 , 70) | (0.33 , 1 , 3) | (1 , 3 , 5) | (0.33 , 1 , 3) | (1 , 3 , 5) | (3 , 5 , 5) |
| PS12 | Fluidized bed dryer | (1603.23 , 3178.27 , 5423.7) | (40 , 60 , 80) | (0.33 , 1 , 3) | (1 , 3 , 5) | (0.33 , 1 , 3) | (1 , 3 , 5) | (0.33 , 1 , 3) |

| HEATING SUBSYSTEM | | SUB-CRITERIA | | | | | | |
|---|---|---|---|---|---|---|---|---|
| ID | Technology | $C_{12}$ | $C_{14}$ | $C_{21}$ | $C_{22}$ | $C_{31}$ | $C_{32}$ | $C_{33}$ |
| HS01 | Boiler/heater-non renewable en | (70 , 77.5 , 85) | (0 , 0 , 0) | (0.33 , 1 , 3) | (0.33 , 1 , 3) | (0.33 , 1 , 3) | (0.33 , 1 , 3) | (0.33 , 1 , 3) |
| HS02 | Boiler-renewable energy | (70 , 72.5 , 75) | (100 , 100 , 100) | (0.33 , 1 , 3) | (0.33 , 1 , 3) | (0.33 , 1 , 3) | (0.33 , 1 , 3) | (0.33 , 1 , 3) |
| HS03 | Boiler-mixed type | (70 , 75 , 80) | (30 , 50 , 70) | (0.33 , 1 , 3) | (0.33 , 1 , 3) | (0.33 , 1 , 3) | (0.33 , 1 , 3) | (0.2 , 0.33 , 1) |
| HS04 | Solar collector | (40 , 50 , 60) | (100 , 100 , 100) | (1 , 3 , 5) | (1 , 3 , 5) | (0.2 , 0.33 , 1) | (0.2 , 0.33 , 1) | (0.2 , 0.33 , 1) |
| HS05 | Heat pump | (90 , 95 , 100) | (0 , 0 , 0) | (0.2 , 0.33 , 1) | (0.2 , 0.33 , 1) | (1 , 3 , 5) | (0.2 , 0.33 , 1) | (0.2 , 0.33 , 1) |

| HEAT RECOVERY SUBSYSTEM | | SUB-CRITERIA | | | | | |
|---|---|---|---|---|---|---|---|
| ID | Technology | $C_{13}$ | $C_{21}$ | $C_{22}$ | $C_{31}$ | $C_{32}$ | $C_{33}$ |
| RS01 | No heat recovery | (0 , 0 , 0) | (0.2 , 0.2 , 0.33) | (0.2 , 0.2 , 0.33) | (1 , 3 , 5) | (0.2 , 0.33 , 1) | (1 , 3 , 5) |
| RS02 | Exhaust air recirculation | (15 , 32.5 , 50) | (0.2 , 0.33 , 1) | (0.33 , 1 , 3) | (0.2 , 0.33 , 1) | (1 , 3 , 5) | (0.33 , 1 , 3) |
| RS03 | Exhaust air heat exchanger | (10 , 20 , 30) | (1 , 3 , 5) | (1 , 3 , 5) | (1 , 3 , 5) | (0.2 , 0.33 , 1) | (0.2 , 0.33 , 1) |

Figure 5-5. Justification of the selected subsystem technologies for drying of coconut

Figure 5-6 shows the results of the final selection of the technologies.

| PROCESSING SUBSYSTEM | | FUZZY RATING | DEFFUZIFICATION | | | RANKING |
|---|---|---|---|---|---|---|
| ID | Technology | $r_{PS}$ | $x_{PS}$ | $y_{PS}$ | $R_{PS}$ | |
| PS05 | Rotary steam tube dryer | (-1.81 , 0.5 , 32.12) | 10.27 | 0.344 | 10.276 | 1 |
| PS11 | Direct rotary dryer | (-2.23 , 0.27 , 29.32) | 9.119 | 0.34 | 9.126 | 2 |
| PS12 | Fluidized bed dryer | (-2.24 , 0.24 , 29.04) | 9.011 | 0.339 | 9.018 | 3 |
| PS04 | Contact conveyor dryers | (-1.12 , 0.37 , 26.21) | 8.487 | 0.343 | 8.494 | 4 |
| PS09 | Direct conveyor dryers | (-1.72 , 0.35 , 26.27) | 8.302 | 0.343 | 8.309 | 5 |
| PS02 | Contact tunnel dryer | (-0.88 , 0.31 , 14.38) | 4.604 | 0.348 | 4.618 | 6 |
| PS08 | Direct tunnel dryer | (-1.48 , 0.2 , 13.29) | 4.004 | 0.344 | 4.019 | 7 |
| **HEATING SUBSYSTEM** | | **FUZZY RATING** | **DEFFUZIFICATION** | | | **RANKING** |
| ID | Technology | $r_{HS}$ | $x_{HS}$ | $y_{HS}$ | $R_{HS}$ | |
| HS02 | Boiler-renewable energy | (-1.36 , 0.94 , 31.4) | 10.326 | 0.353 | 10.332 | 1 |
| HS05 | Heat pump | (-0.43 , 1.01 , 28.51) | 9.694 | 0.356 | 9.7 | 2 |
| HS01 | Boiler/heater-non renewable ener | (-1.38 , 0.58 , 25.72) | 8.304 | 0.348 | 8.311 | 3 |
| HS03 | Boiler-mixed type | (-1.38 , 0.71 , 24.51) | 7.949 | 0.353 | 7.957 | 4 |
| HS04 | Solar collector | (-1.45 , 0.37 , 17.8) | 5.57 | 0.348 | 5.581 | 5 |
| **HEAT RECOVERY SUBSYSTEM** | | **FUZZY RATING** | **DEFFUZIFICATION** | | | **RANKING** |
| ID | Technology | $r_{RS}$ | $x_{RS}$ | $y_{RS}$ | $R_{RS}$ | |
| RS02 | Exhaust air recirculation | (-1.14 , 0.58 , 42.2) | 13.883 | 0.342 | 13.887 | 1 |
| RS03 | Exhaust air heat exchanger | (-1.25 , 0.17 , 33.05) | 10.655 | 0.337 | 10.661 | 2 |
| RS01 | No heat recovery | (-0.2 , 0.21 , 16.78) | 5.599 | 0.342 | 5.609 | 3 |

Figure 5-6. Defuzzification and ranking of the subsystem technologies for drying of coconut

Under the sustainable point of this study, it can be seen that rotary steam tube dryer is the most preferable one, followed by direct rotary dryer. Direct tunnel dryer is the least appropriate technology for drying of coconut. For heating subsystem and heat recovery subsystem, boiler using renewable energy and exhaust air recirculation are respectively the most preferable technologies.

However, considering the overall drying system, the combination of direct rotary dryer with renewable energy boiler and exhaust air recirculation is the most recommended technology. The ratings and rankings of the overall systems are partly presented in Figure 5-7 and fully presented in Annex 4-9.

| SYSTEM ALTERNATIVE | | SUBSYSTEM | | | FUZZY RATING | DEFFUZIFICATION | | | RANKING |
|---|---|---|---|---|---|---|---|---|---|
| ID | Technology | PS | HS | RS | $r_A$ | $x_A$ | $y_A$ | $R_A$ | |
| A185 | Direct rotary dryer - Boiler-renewabl | PS11 | HS02 | RS02 | (-0.77 , 0.5 , 74.51) | 24.74 | 0.34 | 24.75 | 1 |
| A203 | Fluidized bed dryer - Boiler-renewab | PS12 | HS02 | RS02 | (-0.78 , 0.48 , 74.15) | 24.62 | 0.34 | 24.62 | 2 |
| A186 | Direct rotary dryer - Boiler-renewabl | PS11 | HS02 | RS03 | (-0.78 , 0.45 , 72.03) | 23.9 | 0.34 | 23.9 | 3 |
| A204 | Fluidized bed dryer - Boiler-renewab | PS12 | HS02 | RS03 | (-0.78 , 0.43 , 71.67) | 23.77 | 0.34 | 23.77 | 4 |
| A076 | Rotary steam tube dryer - Boiler-rene | PS05 | HS02 | RS01 | (-0.61 , 0.6 , 71.19) | 23.73 | 0.34 | 23.73 | 5 |
| A149 | Direct conveyor dryers - Boiler-renew | PS09 | HS02 | RS02 | (-0.65 , 0.55 , 70.61) | 23.5 | 0.34 | 23.51 | 6 |
| A182 | Direct rotary dryer - Boiler/heater-no | PS11 | HS01 | RS02 | (-0.78 , 0.39 , 69.89) | 23.17 | 0.34 | 23.17 | 7 |
| A200 | Fluidized bed dryer - Boiler/heater-n | PS12 | HS01 | RS02 | (-0.78 , 0.37 , 69.52) | 23.04 | 0.34 | 23.04 | 8 |
| A188 | Direct rotary dryer - Boiler-mixed typ | PS11 | HS03 | RS02 | (-0.78 , 0.43 , 68.91) | 22.85 | 0.34 | 22.86 | 9 |
| A206 | Fluidized bed dryer - Boiler-mixed ty | PS12 | HS03 | RS02 | (-0.78 , 0.41 , 68.54) | 22.72 | 0.34 | 22.73 | 10 |

Figure 5-7. Ratings and rankings of the system technologies for drying of coconut

### 5.2.2 Selection for technology change of the existing facility

A company in Ben Tre province, Vietnam, was chosen as the base-case alternative for the technology change application. Some basic information of this company is shown below:


Figure 5-8. The products of Thanh Vinh coconut processing factory

- Name of the company: Thanh Vinh coconut processing factory
- Address: An Hiep commune, Chau Thanh district, Ben Tre province
- Number of employees: 109 people

Table 5-2. Production information of Thanh Vinh coconut processing factory[6]

| ***Parameter*** | ***Unit*** | ***Quantity*** |
|---|---|---|
| Product (desiccated coconut) | Tons/month | 488 |
| Material (copra) | Tons/month | 1,185 |
| Electric | kWh/ton product | 261 |
| Water | $m^3$/ton product | 8 |
| Fuel (rice husk) | Tons/ton product | 8 |

[6]Source: Cleaner production assessment report – Thanh Vinh coconut processing factory implemented by Ho Chi Minh city Environmental Protection Agency (HEPA) in 2008

The existing drying system of the factory is fluid bed dryer type, using biomass steam boiler to heat drying air (see the schematic diagram and pictures in Figure 5-9). The drying process parameters are as follows:

- Design capacity: 1,000 tons/month
- Actual capacity: 600 tons/month
- Moisture content of wet feed: 50 - 60% (seasonal)
- Moisture content of dried product: 3%
- Particle size: fine and medium
- Retention time of the material within the dryer: 25 - 30 minutes

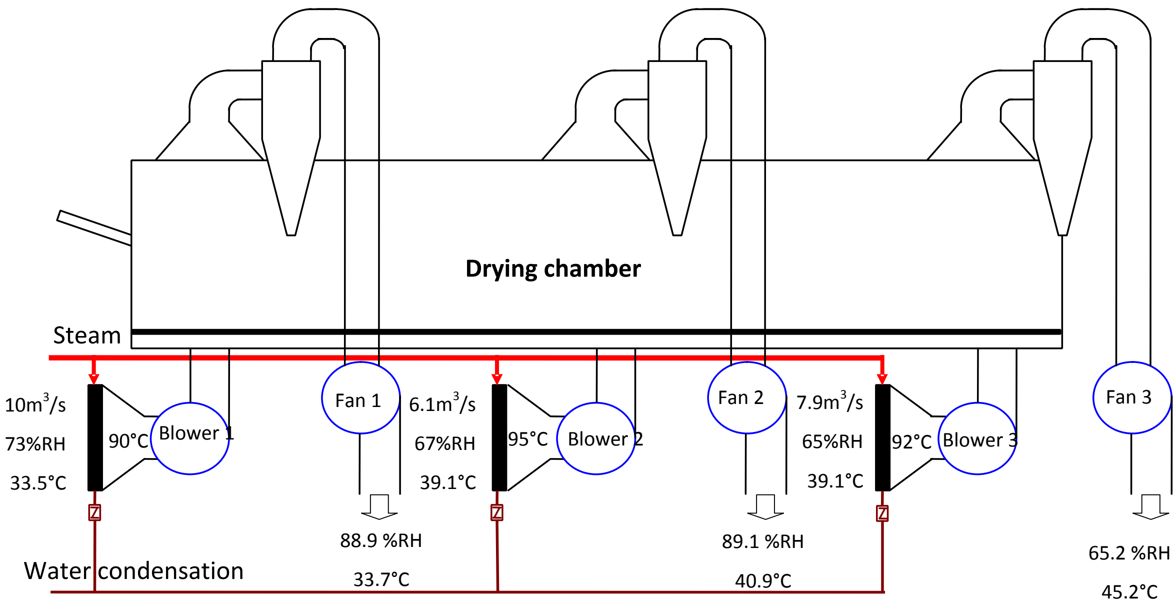


Figure 5-9. Schematic diagram and some pictures of the existing coconut drying system

Additionally, an energy audit was carried out for the drying process and the most important results are shown in Figure 5-10 below.

The audit results also showed that drying is the most energy-intensive operation of the manufacturing process. It accounts up to 68% of the total electric consumption, and 100% of the total thermal energy consumption of the company. Although it takes advantage of the biomass fuel largely available in the area, the inefficient energy utilization in the drying process still causes significant energy loss and therefore significant operation costs.

| Parameter | Unit | Value |
|---|---|---|
| **Operating data** | | |
| Type of fuel | | Rice husk |
| LHV of fuel | MJ/kg | 12.5 - 14 |
| Fuel consumption | kg/s | 0.21 |
| Heat recovery ratio | % | 0 |
| **State 0: ambient air** | | |
| Ambient air temperature | oC | 33 - 35 |
| Relative humidity of ambient air | % | 65 - 73 |
| **State 1: inlet drying air** | | |
| Drying air mass flowrate | $m^3/s$ | 24 |
| Drying air temperature | oC | 95 - 100 |
| Wet bulb temperature of drying air | oC | 37 - 43 |
| **State 2: outlet drying air (exhaust air)** | | |
| Exhaust air temperature | oC | 39 - 45 |
| Relative humidity | % | 65 - 89 |
| **Feed parameters** | | |
| Initial moisture content of feed on wet basis | % | 50 - 60 |
| Material mass flowrate | kg/batch o | 0.56 |
| **Product parameters** | | |
| Final moisture content of product on wet ba | % | 3 |

Figure 5-10. Thermodynamic data of the base-case alternative for coconut drying

From the audit results, STEC, thermal efficiency, heat recovery ratio and renewable energy ratio of the existing drying system were calculated. The performances of the base-case alternative with respect to environmental, economic, and social criteria have been then determined as in Figure 5-11.

| | Criteria | PSbc | HSbc | RSbc |
|---|---|---|---|---|
| C11 | Specific thermal energy consumption | (3150.67 , 4806.55 , 7075.65) | - | - |
| C12 | Thermal energy efficiency | (34.49 , 51.47 , 79.75) | (28.15 , 51.86 , 88.7) | - |
| C13 | Heat recovery ratio | - | - | (0 , 0 , 0) |
| C14 | Renewable energy utilization | - | (100 , 100 , 100) | - |
| C21 | Investment cost | (0.33 , 1 , 3) | (0.33 , 1 , 3) | (0.2 , 0.2 , 0.33) |
| C22 | Operation cost | (1 , 3 , 5) | (0.33 , 1 , 3) | (0.2 , 0.2 , 0.33) |
| C31 | Final product quality | (0.33 , 1 , 3) | (0.33 , 1 , 3) | (1 , 3 , 5) |
| C32 | Fire hazard and explosion hazard | (1 , 3 , 5) | (0.33 , 1 , 3) | (0.2 , 0.33 , 1) |
| C33 | Convience of installation and operation | (0.33 , 1 , 3) | (0.33 , 1 , 3) | (1 , 3 , 5) |

Figure 5-11. Justification of the base-case alternative for coconut drying

The final selection process is then repeated using the base-cased normalization method. The intermediate results of this calculation process can be found in Annex 1-6 to Annex 1-8. Figure 5-12 and Figure 5-13 respectively present the fuzzy ratings and final rankings of the proposed subsystem and overall system alternatives with reference to the base-case alternative.

| PROCESSING SUBSYSTEM | | FUZZY RATING | DEFFUZIFICATION | | | RANKING |
|---|---|---|---|---|---|---|
| ID | Technology | $r_{PS}$ | $x_{PS}$ | $y_{PS}$ | $R_{PS}$ | |
| PSbc | Fluidized bed dryer | (-1.95 , 0.22 , 30.7) | 9.658 | 0.338 | 9.664 | 4 |
| PS05 | Rotary steam tube dryer | (-1.71 , 0.62 , 34.94) | 11.283 | 0.345 | 11.288 | 1 |
| PS11 | Direct rotary dryer | (-2.07 , 0.4 , 31.83) | 10.053 | 0.342 | 10.058 | 2 |
| PS12 | Fluidized bed dryer | (-2.08 , 0.33 , 30.77) | 9.676 | 0.341 | 9.682 | 3 |
| PS04 | Contact conveyor dryers | (-1.01 , 0.43 , 27.64) | 9.021 | 0.344 | 9.028 | 4 |
| PS09 | Direct conveyor dryers | (-1.51 , 0.42 , 27.69) | 8.869 | 0.344 | 8.875 | 5 |
| PS02 | Contact tunnel dryer | (-0.82 , 0.36 , 15.48) | 5.005 | 0.349 | 5.017 | 6 |
| PS08 | Direct tunnel dryer | (-1.32 , 0.26 , 15) | 4.647 | 0.345 | 4.659 | 7 |
| **HEATING SUBSYSTEM** | | **FUZZY RATING** | **DEFFUZIFICATION** | | | **RANKING** |
| ID | Technology | $r_{HS}$ | $x_{HS}$ | $y_{HS}$ | $R_{HS}$ | |
| HSbc | Boiler-renewable energy | (-1.44 , 0.72 , 35.36) | 11.546 | 0.347 | 11.551 | 2 |
| HS05 | Heat pump | (-0.46 , 1.18 , 35.62) | 12.116 | 0.354 | 12.121 | 1 |
| HS02 | Boiler-renewable energy | (-1.43 , 0.92 , 33.47) | 10.986 | 0.351 | 10.992 | 2 |
| HS01 | Boiler/heater-non renewable ener | (-1.45 , 0.68 , 30.39) | 9.877 | 0.348 | 9.884 | 3 |
| HS03 | Boiler-mixed type | (-1.44 , 0.77 , 28.15) | 9.158 | 0.351 | 9.165 | 4 |
| HS04 | Solar collector | (-1.63 , 0.27 , 18.8) | 5.813 | 0.344 | 5.824 | 5 |
| **HEAT RECOVERY SUBSYSTEM** | | **FUZZY RATING** | **DEFFUZIFICATION** | | | **RANKING** |
| ID | Technology | $r_{RS}$ | $x_{RS}$ | $y_{RS}$ | $R_{RS}$ | |
| RSbc | No heat recovery | (-0.31 , 0.1 , 13.35) | 4.38 | 0.338 | 4.393 | 3 |
| RS02 | Exhaust air recirculation | (-1.77 , 0.3 , 40.66) | 13.062 | 0.338 | 13.067 | 1 |
| RS03 | Exhaust air heat exchanger | (-1.97 , -0.59 , 30.83) | 9.425 | 0.319 | 9.431 | 2 |
| RS01 | No heat recovery | (-0.31 , 0.1 , 13.35) | 4.38 | 0.338 | 4.393 | 3 |

Figure 5-12. Defuzzification of the subsystem technologies with reference to the base-case alternative for coconut drying

The processing technology of the base-case (the first row highlighted in yellow in Figure 5-12) ranks 4$^{th}$ out of 7 proposed technologies, while the same technology recommended by the DSS (PS12) ranks 3$^{rd}$. This indicates that the existing drying system is still working at a low sustainability and can be improved. On the other hand, there are 2 other technologies that may be more preferable than the existing technology in terms of sustainability including rotary steam tube dryer and direct rotary dryer.

The heating technology of the base-case alternative ranks 2$^{nd}$ in the list of heating subsystem thanks to the use of renewable energy in the process. Rank 3$^{rd}$ in the list, the existing heat recovery technology could be further improved to exhaust air recirculation or exhaust air heat exchanger in order to increase the sustainability of the process.

Considering the overall technology, the base-case alternative ranks 18th out of 51 alternatives proposed by the DSS as displayed in Figure 5-13 and fully given in Annex 4-10.

| SYSTEM ALTERNATIVE | | SUBSYSTEM | | | FUZZY RATING | DEFFUZIFICATION | | | RANKING |
|---|---|---|---|---|---|---|---|---|---|
| ID | Technology | PS | HS | RS | $r_A$ | $x_A$ | $y_A$ | $R_A$ | |
| Abc | Fluidized bed dryer - Boiler-renewab | PSbc | HSbc | RSbc | (-0.66 , 0.35 , 71.67) | 23.79 | 0.34 | 23.79 | 18 |
| A185 | Direct rotary dryer - Boiler-renewabl | PS11 | HS02 | RS02 | (-0.79 , 0.54 , 78.99) | 26.25 | 0.34 | 26.25 | 1 |
| A203 | Fluidized bed dryer - Boiler-renewab | PS12 | HS02 | RS02 | (-0.79 , 0.5 , 77.63) | 25.78 | 0.34 | 25.78 | 2 |
| A182 | Direct rotary dryer - Boiler/heater-no | PS11 | HS01 | RS02 | (-0.79 , 0.47 , 76.49) | 25.39 | 0.34 | 25.39 | 3 |
| A186 | Direct rotary dryer - Boiler-renewabl | PS11 | HS02 | RS03 | (-0.8 , 0.45 , 76.33) | 25.32 | 0.34 | 25.33 | 4 |
| A076 | Rotary steam tube dryer - Boiler-rene | PS05 | HS02 | RS01 | (-0.6 , 0.65 , 75.55) | 25.2 | 0.34 | 25.21 | 5 |
| A200 | Fluidized bed dryer - Boiler/heater-n | PS12 | HS01 | RS02 | (-0.79 , 0.43 , 75.13) | 24.92 | 0.34 | 24.93 | 6 |
| A204 | Fluidized bed dryer - Boiler-renewab | PS12 | HS02 | RS03 | (-0.8 , 0.41 , 74.97) | 24.86 | 0.34 | 24.86 | 7 |
| A188 | Direct rotary dryer - Boiler-mixed typ | PS11 | HS03 | RS02 | (-0.79 , 0.49 , 74.66) | 24.79 | 0.34 | 24.79 | 8 |
| A149 | Direct conveyor dryers - Boiler-rene | PS09 | HS02 | RS02 | (-0.65 , 0.55 , 73.69) | 24.53 | 0.34 | 24.54 | 9 |
| A183 | Direct rotary dryer - Boiler/heater-no | PS11 | HS01 | RS03 | (-0.8 , 0.38 , 73.82) | 24.47 | 0.34 | 24.47 | 10 |

Figure 5-13. Ratings and rankings of the system technologies with reference to the base-case alternative for coconut drying

## 5.3 SELECTION OF CASSAVA STARCH DRYERS

Cassava starch is obtained from the root of cassava plants. The quality of cassava starch produced can be affected by the fresh root quality and the end user' requirement. General specifications of cassava starch are summarized in Table 5-3.

Table 5-3. General specification of natural cassava starch

| ***Attribute*** | ***Value*** |
|---|---|
| Moisture content (% maximum) | 13 |
| Starch content (% minimum) | 85 |
| Ash (% maximum) | 0.2 |
| pH | 5.0 - 7.0 |
| Whiteness (Kett scale, minimum) | 90 |
| Viscosity Barbender unit , BU, minimum at 6% dry weight concentration | 600 |
| Sulfur dioxide content (ppm maximum) | 30 |

| *Attribute* | *Value* |
|---|---|
| Cyanide content | Negative |
| Appearance | White, no speck, fresh odor |

Source: Breuninger et al. (2009)

The cassava starch production process is highly varied and always complies well with the production scale. The general production process of cassava starch of most large scale factories (about 50 tons product/day) is illustrated in Figure 5-14.

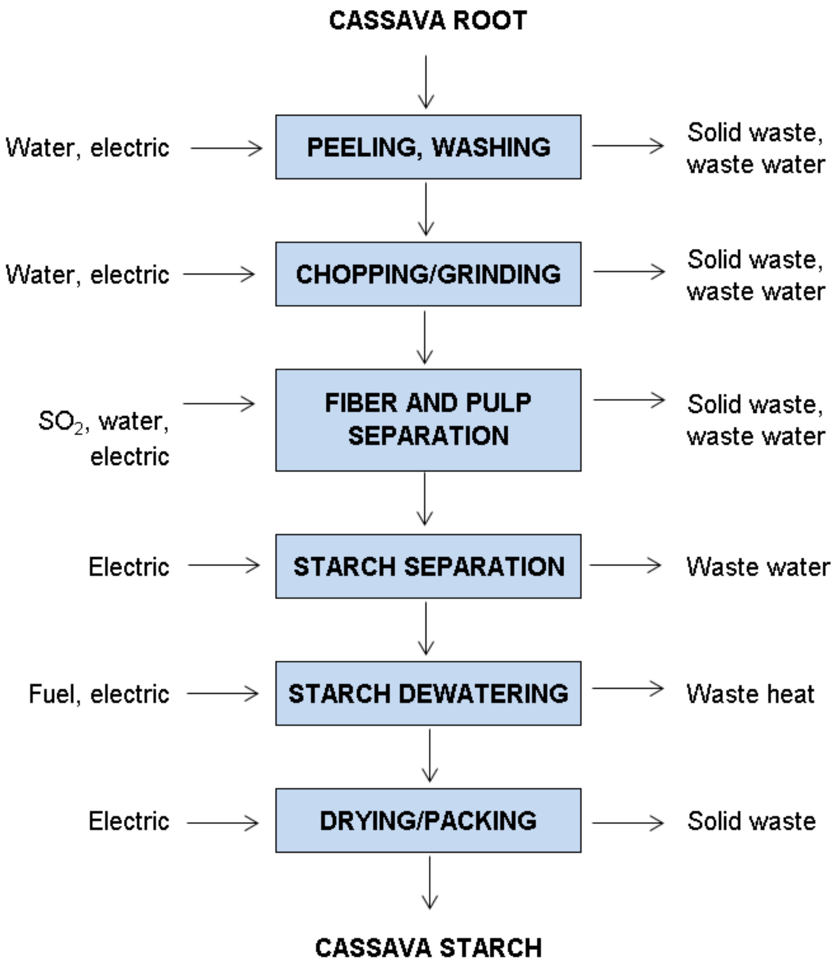


Figure 5-14. General production process of cassava starch

The production of the cassava starch consumes a large amount of thermal energy, mainly in the drying process. The specific electrical and thermal energy consumption for production of cassava starch have been found to be 608 ± 135 MJ/t and 1303 ± 324 MJ/t respectively

(Chavalparit & Ongwandee, 2009). Cassava starch dryers are commercially available in a number of forms including sun drying (for small scale production), static bed drying, rotary drying and pneumatic drying and solar drying. Among them, pneumatic drying is largely found in practice in Vietnam.

### 5.3.1 Selection of new facility

In the new facility selection, data for the selecting process is retrieved from the database. The material and product specifications of cassava starch specified for the preliminary selection step is shown in Figure 5-15.

| | |
|---|---|
| Name: | **Cassava starch** |
| Product ID: | **DA15.333.5** |
| Physical form of feed: | **Fine powder/granular** |
| Nature of wet feed: | **Free flowing, non-cohesive, loose** |
| Special requirements of product: | **Uncontaminated** |
| Allowable drying temperature: | **Bellow boiling temperature** |
| | **Above boiling temperature** |
| | **Below freezing temperature** |
| Product throughput: | **Wide range** |
| Mode of upstream and downstream operations: | **Batch or continuous** |

Figure 5-15. Specification of cassava starch for preliminary selection

The preliminary selection of cassava starch dryers results in 10 processing technologies, 6 heating technologies and 3 heat recovery technologies (Figure 5-16).

| PROCESSING SUBSYSTEM | | | HEATING SUBSYSTEM | | | HEAT RECOVERY SUBSYSTEM | | |
|---|---|---|---|---|---|---|---|---|
| No. | ID | Technology | No. | ID | Technology | No. | ID | Technology |
| 1 | PS01 | Contact cabinet dryer | 1 | HS01 | Boiler/heater-non renewable e | 1 | RS01 | No heat recovery |
| 2 | PS02 | Contact tunnel dryer | 2 | HS02 | Boiler-renewable energy | 2 | RS02 | Exhaust air recirculation |
| 3 | PS03 | Plate dryer | 3 | HS03 | Boiler-mixed type | 3 | RS03 | Exhaust air heat exchanger |
| 4 | PS05 | Rotary steam tube dryer | 4 | HS04 | Solar collector | | | |
| 5 | PS07 | Direct cabinet dryer | 5 | HS05 | Heat pump | | | |
| 6 | PS08 | Direct tunnel dryer | 6 | HS06 | Refrigeration plant | | | |
| 7 | PS11 | Direct rotary dryer | | | | | | |
| 8 | PS12 | Fluidized bed dryer | | | | | | |
| 9 | PS15 | Pneumatic flash dryer | | | | | | |
| 10 | PS16 | Freeze dryer | | | | | | |

Figure 5-16. Pre-selected subsystem technologies for drying of cassava starch

These subsystem technologies configure 64 overall system technologies. Figure 5-17 is an extract of the data sheet of pre-selected system technologies.

| No. | ID | Technology | PS | HS | RS |
|---|---|---|---|---|---|
| 1 | A001 | Contact cabinet dryer - Boiler/heater-non renewable energy - No heat recovery | PS01 | HS01 | RS01 |
| 2 | A004 | Contact cabinet dryer - Boiler-renewable energy - No heat recovery | PS01 | HS02 | RS01 |
| 3 | A007 | Contact cabinet dryer - Boiler-mixed type - No heat recovery | PS01 | HS03 | RS01 |
| 4 | A019 | Contact tunnel dryer - Boiler/heater-non renewable energy - No heat recovery | PS02 | HS01 | RS01 |
| 5 | A022 | Contact tunnel dryer - Boiler-renewable energy - No heat recovery | PS02 | HS02 | RS01 |
| 6 | A025 | Contact tunnel dryer - Boiler-mixed type - No heat recovery | PS02 | HS03 | RS01 |
| 7 | A037 | Plate dryer - Boiler/heater-non renewable energy - No heat recovery | PS03 | HS01 | RS01 |
| 8 | A040 | Plate dryer - Boiler-renewable energy - No heat recovery | PS03 | HS02 | RS01 |
| 9 | A043 | Plate dryer - Boiler-mixed type - No heat recovery | PS03 | HS03 | RS01 |
| 10 | A073 | Rotary steam tube dryer - Boiler/heater-non renewable energy - No heat recovery | PS05 | HS01 | RS01 |

Figure 5-17. Pre-selected system technologies for drying of cassava starch

The subsystem technologies have been then taken into the rating and ranking process in the final selection step using the aggregated normalization method. Thermodynamic properties of the drying processes are as shown in Annex 5-1. The justification data of the subsystem technology alternatives with respect to energy, economic and social performances and the intermediate results of the final selection step can be found in Annex 5-2 to Annex 5-5. The ratings and rankings of the subsystem technologies are finally shown in Figure 5-18 below.

| PROCESSING SUBSYSTEM | | FUZZY RATING | DEFFUZIFICATION | | | RANKING |
|---|---|---|---|---|---|---|
| ID | Technology | $r_{PS}$ | $x_{PS}$ | $y_{PS}$ | $R_{PS}$ | |
| PS15 | Pneumatic flash dryer | (-1.6 , 0.56 , 25.85) | 8.27 | 0.348 | 8.278 | 1 |
| PS05 | Rotary steam tube dryer | (-1.44 , 0.51 , 25.2) | 8.091 | 0.347 | 8.098 | 2 |
| PS11 | Direct rotary dryer | (-1.92 , 0.27 , 22.49) | 6.948 | 0.342 | 6.957 | 3 |
| PS12 | Fluidized bed dryer | (-1.92 , 0.2 , 21.61) | 6.63 | 0.34 | 6.639 | 4 |
| PS03 | Plate dryer | (-0.89 , 0.51 , 19.4) | 6.341 | 0.351 | 6.351 | 5 |
| PS01 | Contact cabinet dryer | (-0.7 , 0.49 , 14.54) | 4.781 | 0.356 | 4.794 | 6 |
| PS07 | Direct cabinet dryer | (-1.33 , 0.47 , 14.6) | 4.579 | 0.355 | 4.593 | 7 |
| PS16 | Freeze dryer | (-1.7 , -0.31 , 15.45) | 4.478 | 0.317 | 4.49 | 8 |
| PS02 | Contact tunnel dryer | (-0.7 , 0.3 , 11.76) | 3.789 | 0.351 | 3.805 | 9 |
| PS08 | Direct tunnel dryer | (-1.34 , 0.19 , 11.31) | 3.387 | 0.346 | 3.405 | 10 |
| **HEATING SUBSYSTEM** | | **FUZZY RATING** | **DEFFUZIFICATION** | | | **RANKING** |
| ID | Technology | $r_{HS}$ | $x_{HS}$ | $y_{HS}$ | $R_{HS}$ | |
| HS02 | Boiler-renewable energy | (-1.01 , 1.13 , 29.1) | 9.74 | 0.358 | 9.746 | 1 |
| HS05 | Heat pump | (-0.31 , 1.05 , 21.72) | 7.485 | 0.363 | 7.494 | 2 |
| HS01 | Boiler/heater-non renewable ener | (-1.04 , 0.69 , 22.25) | 7.303 | 0.354 | 7.312 | 3 |
| HS03 | Boiler-mixed type | (-1.03 , 0.86 , 21.69) | 7.176 | 0.359 | 7.185 | 4 |
| HS04 | Solar collector | (-0.83 , 0.65 , 18.44) | 6.088 | 0.356 | 6.098 | 5 |
| HS06 | Refrigeration plant | (-0.71 , -0.06 , 12.98) | 4.072 | 0.33 | 4.085 | 6 |
| **HEAT RECOVERY SUBSYSTEM** | | **FUZZY RATING** | **DEFFUZIFICATION** | | | **RANKING** |
| ID | Technology | $r_{RS}$ | $x_{RS}$ | $y_{RS}$ | $R_{RS}$ | |
| RS02 | Exhaust air recirculation | (-1.14 , 0.58 , 42.2) | 13.883 | 0.342 | 13.887 | 1 |
| RS03 | Exhaust air heat exchanger | (-1.25 , 0.17 , 33.05) | 10.655 | 0.337 | 10.661 | 2 |
| RS01 | No heat recovery | (-0.2 , 0.21 , 16.78) | 5.599 | 0.342 | 5.609 | 3 |

Figure 5-18. Ratings and rankings of the subsystem technologies for drying of cassava starch

The result shows that, under the sustainable viewpoint of this study, pneumatic flash dryer appears the most promising solution, followed by rotary steam tube dryer. Freeze dryer and tunnel dryer are the least appropriate technologies. For heating subsystem and heat recovery subsystem, renewable energy boiler and exhaust air recirculation are respectively the most referable technologies.

Considered the whole drying system, the ranking list is partly presented in Figure 5-19 and fully displayed in Annex 5-9.

| SYSTEM ALTERNATIVE | | SUBSYSTEM | | | FUZZY RATING | DEFFUZIFICATION | | | RANKING |
|---|---|---|---|---|---|---|---|---|---|
| ID | Technology | PS | HS | RS | $r_A$ | $x_A$ | $y_A$ | $R_A$ | |
| A257 | Pneumatic flash dryer - Boiler-renew | PS15 | HS02 | RS02 | (-0.58 , 0.73 , 68.2) | 22.78 | 0.34 | 22.78 | 1 |
| A258 | Pneumatic flash dryer - Boiler-renew | PS15 | HS02 | RS03 | (-0.59 , 0.68 , 65.71) | 21.94 | 0.34 | 21.94 | 2 |
| A185 | Direct rotary dryer - Boiler-renewabl | PS11 | HS02 | RS02 | (-0.66 , 0.55 , 63.9) | 21.27 | 0.34 | 21.27 | 3 |
| A254 | Pneumatic flash dryer - Boiler/heater | PS15 | HS01 | RS02 | (-0.58 , 0.6 , 62.62) | 20.88 | 0.34 | 20.88 | 4 |
| A203 | Fluidized bed dryer - Boiler-renewab | PS12 | HS02 | RS02 | (-0.66 , 0.51 , 62.78) | 20.88 | 0.34 | 20.88 | 5 |
| A260 | Pneumatic flash dryer - Boiler-mixed | PS15 | HS03 | RS02 | (-0.58 , 0.65 , 62.17) | 20.75 | 0.34 | 20.75 | 6 |
| A256 | Pneumatic flash dryer - Boiler-renew | PS15 | HS02 | RS01 | (-0.52 , 0.69 , 61.3) | 20.49 | 0.34 | 20.49 | 7 |
| A186 | Direct rotary dryer - Boiler-renewabl | PS11 | HS02 | RS03 | (-0.67 , 0.51 , 61.42) | 20.42 | 0.34 | 20.42 | 8 |
| A076 | Rotary steam tube dryer - Boiler-ren | PS05 | HS02 | RS01 | (-0.48 , 0.66 , 60.47) | 20.22 | 0.34 | 20.22 | 9 |
| A255 | Pneumatic flash dryer - Boiler/heater | PS15 | HS01 | RS03 | (-0.59 , 0.56 , 60.14) | 20.04 | 0.34 | 20.04 | 10 |

Figure 5-19. Ratings and rankings of the system technologies for drying of cassava starch

### 5.3.2 Selection for technology change of the existing facility

General information of the factory of the base-case:

- Name: Thanh Vinh tapioca processing enterprise
- Address: Ninh Trung hamlet, Ninh Son commune, Tay Ninh town, Tay Ninh province
- Production capacity: 100 tons/day

The existing drying technology of the factory is of pneumatic dryer type. Drying air is heated up to 150 - 160°C by the biogas boiler. The wet starch is fed into the hot gas stream by the conveyor feeder. The starch is dried during transport in the hot gas stream. At the end of the drying process, dried starch is collected by the cyclone separator system. The existing drying system is schematically presented in Figure 5-20 with some pictures of it.

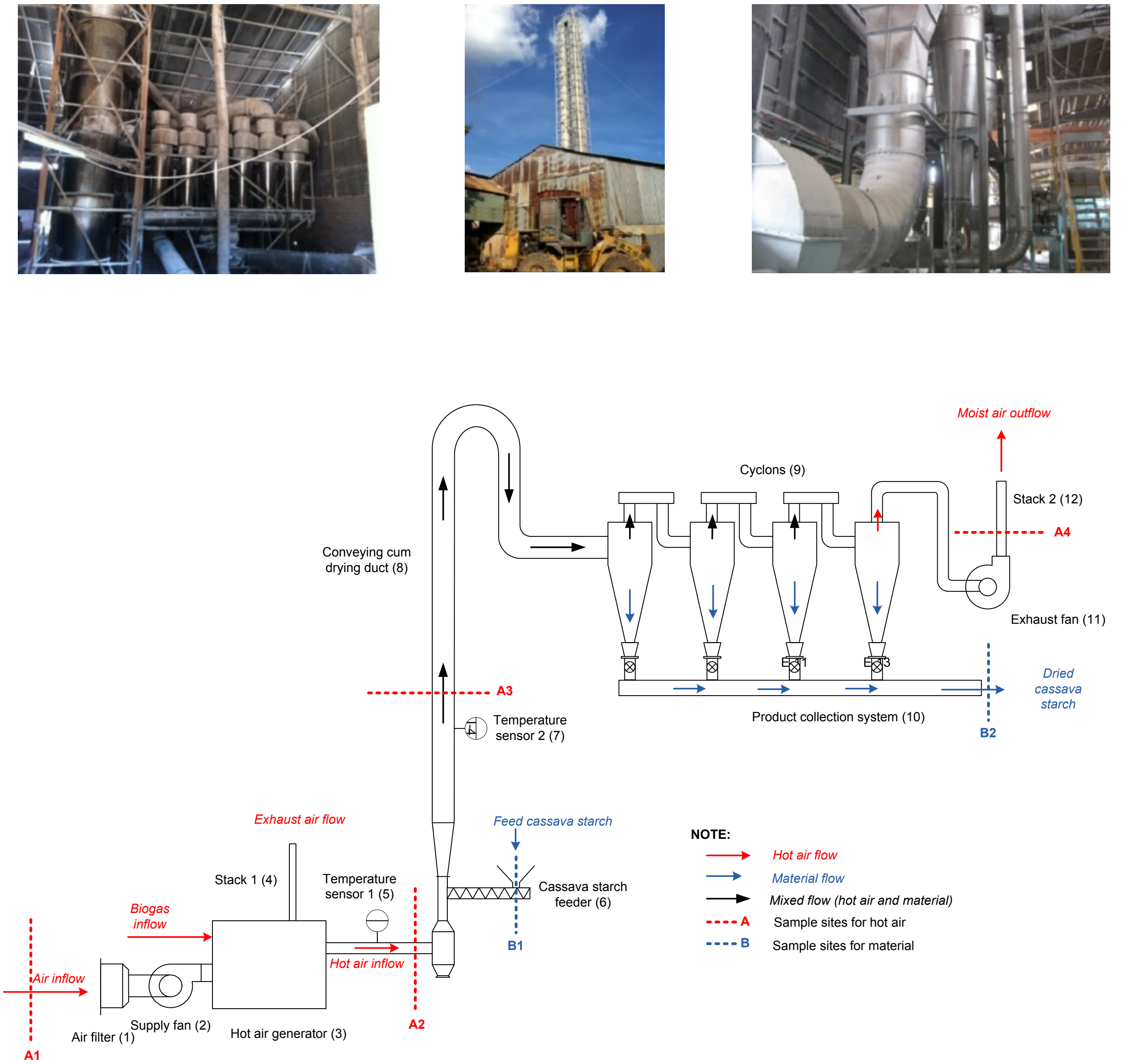


Figure 5-20. Schematic diagram and pictures of the existing starch drying system

The thermodynamic data obtained from the energy audit for the process is summarized in Figure 5-21. The results of STEC calculation and the estimation of thermal efficiency, ratio of renewable energy utilization and ratio of energy recovery, along with the justification with respect to the criteria of economic and social performances of the base-case technology are presented in Figure 5-22.

| Parameter | Notation | Unit | Value |
|---|---|---|---|
| **Operating data** | | | |
| Type of fuel | | | Biogas |
| LHV of fuel | 0 | $Nm^3/s$ | 19.7 - 21.5 |
| Fuel consumption | 0 | $Nm^3/s$ | 0.29 |
| Heat recovery ratio | r | % | 0 |
| **State 0: ambient air** | | | |
| Ambient air temperature | Tamb | °C | 30.2 - 30.7 |
| Relative humidity of ambient air | Yabm | % | 62.9 - 65.2 |
| **State 1: inlet drying air** | | | |
| Drying air mass flowrate | Fa | $m^3/s$ | 40.24 - 42.225 |
| Drying air temperature | Tai | °C | 160 - 170 |
| **State 2: outlet drying air (exhaust air)** | | | |
| Exhaust air temperature | Tao | °C | 47.5 - 48.3 |
| Humidity ratio | y2 | kg/kg dry air | 0.06 - 0.0637 |
| **Feed parameters** | | | |
| Initial moisture content of feed on wet basis | wi | % | 32 - 33 |
| Material mass flowrate | Fi | kg/s | 1.25 |
| **Product parameters** | | | |
| Final moisture content of product on wet ba | wo | % | 13 |

Figure 5-21. Thermodynamic data of the base-case alternative for drying of cassava starch

| | Criteria | PSbc | HSbc | RSbc |
|---|---|---|---|---|
| C11 | Specific thermal energy consumption | (13832.7 , 15333.67 , 21694.14) | - | - |
| C12 | Thermal energy efficiency | (12.54 , 17.82 , 19.83) | (47.41 , 72.07 , 100) | - |
| C13 | Heat recovery ratio | - | - | (0 , 0 , 0) |
| C14 | Renewable energy utilization | - | (100 , 100 , 100) | - |
| C21 | Investment cost | (0.33 , 1 , 3) | (0.33 , 1 , 3) | (0.2 , 0.2 , 0.33) |
| C22 | Operation cost | (0.33 , 1 , 3) | (0.33 , 1 , 3) | (0.2 , 0.2 , 0.33) |
| C31 | Final product quality | (1 , 3 , 5) | (0.33 , 1 , 3) | (1 , 3 , 5) |
| C32 | Fire hazard and explosion hazard | (1 , 3 , 5) | (0.33 , 1 , 3) | (0.2 , 0.33 , 1) |
| C33 | Convience of installation and operation | (0.33 , 1 , 3) | (0.33 , 1 , 3) | (1 , 3 , 5) |

Figure 5-22. Performance of the base-case alternative for drying of cassava starch

The final selection process is then repeated using the base-cased normalization method (Annex 5-6 to Annex 5-8). As can be seen in the resulting spreadsheet in Figure 5-23, the base-case processing technology (the first yellow line) ranks 9$^{th}$ out of 10 proposed technologies, the same ranking of the direct tunnel and freeze drying technologies, whereas the technology proposed by the DSS identical to the base-case (PS05) ranks 2$^{nd}$ in the list. The ranking variation demonstrates the significant inefficiency in energy use of the existing drying process. For the heating subsystem and heat recovery subsystem, the base-case technologies respectively rank 1$^{st}$ and 3$^{rd}$ in the lists, the same ranking with the identical technologies proposed by the DSS.

| PROCESSING SUBSYSTEM | | FUZZY RATING | DEFFUZIFICATION | | | RANKING |
|---|---|---|---|---|---|---|
| ID | Technology | $r_{PS}$ | $x_{PS}$ | $y_{PS}$ | $R_{PS}$ | |
| PSbc | Pneumatic flash dryer | (-2.12 , -0.08 , 18.92) | 5.575 | 0.33 | 5.584 | 9 |
| PS05 | Rotary steam tube dryer | (-1.67 , 1.16 , 36.37) | 11.957 | 0.354 | 11.963 | 1 |
| PS15 | Pneumatic flash dryer | (-1.6 , 1.06 , 33.39) | 10.947 | 0.354 | 10.952 | 2 |
| PS11 | Direct rotary dryer | (-1.94 , 0.74 , 31.25) | 10.017 | 0.349 | 10.023 | 3 |
| PS12 | Fluidized bed dryer | (-1.95 , 0.69 , 30.8) | 9.85 | 0.349 | 9.856 | 4 |
| PS03 | Plate dryer | (-0.92 , 1.07 , 27.83) | 9.327 | 0.358 | 9.334 | 5 |
| PS01 | Contact cabinet dryer | (-0.64 , 1.09 , 24.03) | 8.163 | 0.362 | 8.171 | 6 |
| PS07 | Direct cabinet dryer | (-0.95 , 1.09 , 24.06) | 8.067 | 0.362 | 8.075 | 7 |
| PS02 | Contact tunnel dryer | (-0.65 , 0.76 , 18.86) | 6.323 | 0.359 | 6.333 | 8 |
| PS08 | Direct tunnel dryer | (-0.96 , 0.59 , 16.75) | 5.46 | 0.357 | 5.471 | 9 |
| PS16 | Freeze dryer | (-1.53 , -0.33 , 15.65) | 4.596 | 0.317 | 4.606 | 10 |
| **HEATING SUBSYSTEM** | | **FUZZY RATING** | **DEFFUZIFICATION** | | | **RANKING** |
| ID | Technology | $r_{HS}$ | $x_{HS}$ | $y_{HS}$ | $R_{HS}$ | |
| HSbc | Boiler-renewable energy | (-1.19 , 0.89 , 31.79) | 10.494 | 0.352 | 10.5 | 1 |
| HS02 | Boiler-renewable energy | (-1.19 , 0.9 , 28.91) | 9.54 | 0.354 | 9.547 | 1 |
| HS05 | Heat pump | (-0.38 , 1.05 , 27.73) | 9.47 | 0.357 | 9.476 | 2 |
| HS01 | Boiler/heater-non renewable ener | (-1.21 , 0.63 , 25.18) | 8.201 | 0.35 | 8.209 | 3 |
| HS03 | Boiler-mixed type | (-1.2 , 0.73 , 23.26) | 7.596 | 0.354 | 7.605 | 4 |
| HS06 | Refrigeration plant | (-1.1 , -0.15 , 18.07) | 5.605 | 0.327 | 5.615 | 5 |
| HS04 | Solar collector | (-1.21 , 0.34 , 16.76) | 5.297 | 0.347 | 5.309 | 6 |
| **HEAT RECOVERY SUBSYSTEM** | | **FUZZY RATING** | **DEFFUZIFICATION** | | | **RANKING** |
| ID | Technology | $r_{RS}$ | $x_{RS}$ | $y_{RS}$ | $R_{RS}$ | |
| RSbc | No heat recovery | (-0.31 , 0.1 , 13.35) | 4.38 | 0.338 | 4.393 | 3 |
| RS02 | Exhaust air recirculation | (-1.77 , 0.3 , 40.66) | 13.062 | 0.338 | 13.067 | 1 |
| RS03 | Exhaust air heat exchanger | (-1.97 , -0.59 , 30.83) | 9.425 | 0.319 | 9.431 | 2 |
| RS01 | No heat recovery | (-0.31 , 0.1 , 13.35) | 4.38 | 0.338 | 4.393 | 3 |

Figure 5-23. Ratings and rankings of the subsystem technologies with reference to the base-case alternative for drying of cassava starch

| SYSTEM ALTERNATIVE | | SUBSYSTEM | | | FUZZY RATING | DEFFUZIFICATION | | | RANKING |
|---|---|---|---|---|---|---|---|---|---|
| ID | Technology | PS | HS | RS | $r_A$ | $x_A$ | $y_A$ | $R_A$ | |
| Abc | Pneumatic flash dryer - Boiler-renew | PSbc | HSbc | RSbc | (-0.67 , 0.22 , 53.7) | 17.75 | 0.34 | 17.75 | 51 |
| A257 | Pneumatic flash dryer - Boiler-renew | PS15 | HS02 | RS02 | (-0.64 , 0.93 , 77.27) | 25.85 | 0.34 | 25.85 | 1 |
| A258 | Pneumatic flash dryer - Boiler-renew | PS15 | HS02 | RS03 | (-0.66 , 0.84 , 74.6) | 24.93 | 0.34 | 24.93 | 2 |
| A185 | Direct rotary dryer - Boiler-renewabl | PS11 | HS02 | RS02 | (-0.73 , 0.74 , 74.54) | 24.85 | 0.34 | 24.85 | 3 |
| A254 | Pneumatic flash dryer - Boiler/heater | PS15 | HS01 | RS02 | (-0.65 , 0.85 , 74.23) | 24.81 | 0.34 | 24.81 | 4 |
| A076 | Rotary steam tube dryer - Boiler-ren | PS05 | HS02 | RS01 | (-0.56 , 0.98 , 73.68) | 24.7 | 0.34 | 24.7 | 5 |
| A203 | Fluidized bed dryer - Boiler-renewab | PS12 | HS02 | RS02 | (-0.73 , 0.71 , 73.96) | 24.65 | 0.34 | 24.65 | 6 |
| A260 | Pneumatic flash dryer - Boiler-mixed | PS15 | HS03 | RS02 | (-0.65 , 0.88 , 72.67) | 24.3 | 0.34 | 24.3 | 7 |
| A186 | Direct rotary dryer - Boiler-renewabl | PS11 | HS02 | RS03 | (-0.74 , 0.65 , 71.87) | 23.93 | 0.34 | 23.93 | 8 |
| A255 | Pneumatic flash dryer - Boiler/heater | PS15 | HS01 | RS03 | (-0.66 , 0.76 , 71.56) | 23.89 | 0.34 | 23.89 | 9 |
| A182 | Direct rotary dryer - Boiler/heater-no | PS11 | HS01 | RS02 | (-0.73 , 0.66 , 71.5) | 23.81 | 0.34 | 23.81 | 10 |

Figure 5-24. Ratings and rankings of the system technologies with reference to the base-case alternative for drying of cassava starch

Considering the whole system (Figure 5-24), the existing technology ranks 51$^{th}$ out of 64 technologies recommended by the DSS, whereas the same technology recommended by the DSS (A258) ranks 2$^{nd}$. This again states that the existing drying technology is working at extremely low efficiency and needs to be significantly improved.

## 5.4 CHAPTER FINDINGS

From the results obtained, some important observations can be drawn as follows:

The technologies recommended by the DSS are reasonable and consistent with industrial practices. A small supply market survey has found that most of the technologies proposed by the DSS for drying of coconut and cassava starch are commercially available on the market.

It is apparent that the ranking of the technologies correlates well with human expert assessment. Among the technologies proposed for drying coconut and cassava, rotary dryers, fluid bed dryers and pneumatic dryers, which yield the highest rankings, are indeed technologies commonly found in industrial practices. In the case of freeze dryers, although cassava starch products of very high quality can be yielded by this method, it is among the last rankings in the list due to the notably inefficient energy utilization and high initial investment and operation costs. For this reason, the freeze drying technology is only recommended for high value products such as coffee, enzymes, and food for space missions, military use and sport activities.

| PROCESSING SUBSYSTEM | | | |
|---|---|---|---|
| ID | Technology | APP1 | APP2 |
| PSbc | Fluidized bed dryer | | 4 |
| PS02 | Contact tunnel dryer | 6 | 6 |
| PS04 | Contact conveyor dryers | 4 | 4 |
| PS05 | Rotary steam tube dryer | 1 | 1 |
| PS08 | Direct tunnel dryer | 7 | 7 |
| PS09 | Direct conveyor dryers | 5 | 5 |
| PS11 | Direct rotary dryer | 2 | 2 |
| PS12 | Fluidized bed dryer | 3 | 3 |
| **HEATING SUBSYSTEM** | | | |
| ID | Technology | APP1 | APP2 |
| HSbc | Boiler-renewable energy | | 2 |
| HS01 | Boiler/heater-non renewable e | 3 | 3 |
| HS02 | Boiler-renewable energy | 1 | 2 |
| HS03 | Boiler-mixed type | 4 | 4 |
| HS04 | Solar collector | 5 | 5 |
| HS05 | Heat pump | 2 | 1 |
| **HEAT RECOVERY SUBSYSTEM** | | | |
| ID | Technology | APP1 | APP2 |
| RSbc | No heat recovery | | 3 |
| RS01 | No heat recovery | 3 | 3 |
| RS02 | Exhaust air recirculation | 1 | 1 |
| RS03 | Exhaust air heat exchanger | 2 | 2 |

Case study 1: coconut dryers

| PROCESSING SUBSYSTEM | | | |
|---|---|---|---|
| ID | Technology | APP1 | APP2 |
| PSbc | Pneumatic flash dryer | | 9 |
| PS01 | Contact cabinet dryer | 6 | 6 |
| PS02 | Contact tunnel dryer | 9 | 8 |
| PS03 | Plate dryer | 5 | 5 |
| PS05 | Rotary steam tube dryer | 2 | 1 |
| PS07 | Direct cabinet dryer | 7 | 7 |
| PS08 | Direct tunnel dryer | 10 | 9 |
| PS11 | Direct rotary dryer | 3 | 3 |
| PS12 | Fluidized bed dryer | 4 | 4 |
| PS15 | Pneumatic flash dryer | 1 | 2 |
| PS16 | Freeze dryer | 8 | 10 |
| **HEATING SUBSYSTEM** | | | |
| ID | Technology | APP1 | APP2 |
| HSbc | Boiler-renewable energy | | 1 |
| HS01 | Boiler/heater-non renewable e | 3 | 3 |
| HS02 | Boiler-renewable energy | 1 | 1 |
| HS03 | Boiler-mixed type | 4 | 4 |
| HS04 | Solar collector | 5 | 6 |
| HS05 | Heat pump | 2 | 2 |
| HS06 | Refrigeration plant | 6 | 5 |
| **HEAT RECOVERY SUBSYSTEM** | | | |
| ID | Technology | APP1 | APP2 |
| RSbc | No heat recovery | | 3 |
| RS01 | No heat recovery | 3 | 3 |
| RS02 | Exhaust air recirculation | 1 | 1 |
| RS03 | Exhaust air heat exchanger | 2 | 2 |

Case study 2: cassava starch dryers

Figure 5-25. Comparison of the results obtained from the two methods

As can be seen in the comparison of the rating and ranking results obtained from the two normalization methods in Figure 5-25, although the fuzzy ratings of the alternatives are fluctuant due to the different calculation processes, the rankings obtained from the two normalization methods generally align with each other.

# 6. CONCLUDING REMARKS

In this study, a systematic framework has been developed that provides decision support in selecting suitable thermal process technologies considering sustainability of the process. The selection procedure comprises two main steps: the preliminary selection step which narrows the range of technologies appropriate for the given product, and the final selection step which provides the ratings and rankings of the pre-selected technologies according to a set of criteria. The proposed framework can be applied to support decisions in either the selection of new facilities or the technology change of the existing facilities.

Based on the combination of rule-based technique, analytic hierarchy process and fuzzy logic, the proposed integrative framework is supposed to be applicable for a wide range of thermal processes in food industry including blanching, pasteurization, sterilization, boiling, cooking, drying, etc. Even though rule-based technique, analytic hierarchy process and fuzzy set theory are not new methods in itself, as a combination, they become a new and efficient approach of multiple criteria decision making for thermal process selection.

Rule-based technique is firstly employed in the preliminary selection of technologies for a product under consideration. The selection is principally based upon the technical specifications of the thermal processes and the given products. The configuration of each process system from three separate subsystems ensures to cover the wide range of technologies available on the market. This also helps facilitate the evaluation of energy performance of the process in the final selection step.

In the final selection step, fuzzy analytic hierarchy process is used to define the ratings and rankings of the pre-selected technology alternatives. The parameters for the appraisal of sustainability are aggregated into three major indicators: environmental, economic and social criteria. Energy performance is particularly considered in this step due to the fact that thermal processes are the most energy-intensive unit operation in food manufacturing sector. The rating and ranking algorithms have been enhanced to overcome the challenge of untrustworthy outcomes while selecting from a large number of alternatives. This allows for the selection of the processes having a wide range of technologies that happens in most of the thermal processes.

Dealing with the insufficiency and uncertainty facing in most decision making problems, the data for the rating and ranking procedure is generally specified in triangular fuzzy number. Calculating fuzzy numbers might be troublesome and tedious; however the reliability of the obtained results can be enhanced.

The main advantage of this approach is that it enables a simple AHP selection procedure whereas the complex thermodynamic analyses have been properly settled. The proposed integrative framework has been successfully tested in the development of a decision support system for food dryer selection. Facing the complexity and diversity of the drying process, the decision support system is developed to be comprehensive, yet simple enough for being used by the non-technical person.

The core components of this decision support system are the database of drying technologies and food products and the database of dryer's performance with respect to the energy, economic and social criteria. A huge amount of data has been carefully screened in order to make the databases as exhaustive and consistent as possible.

In the testing of the decision support system, it has been found that the ranking of a set of alternatives can change if a new constituent is introduced into the set of constituents (criteria, sub-criteria or alternatives). For this reason, it is strongly recommended to have a consistent and comprehensive hierarchical criteria system in order to ensure the accuracy and consistency of the results.

The DSS has been successfully implemented in two case studies: selecting coconut dryers and cassava starch dryers. Both the applications for the selection of new facilities and changing the used technologies of the existing facilities were carried out in the case studies.

The technologies recommended by the DSS are reasonable and consistent with industrial practices. Furthermore, the ranking of the technologies correlate well with human expert assessment. It is obvious from the results obtained that although the ratings of the alternatives from the two applications are fluctuant due to the different calculation processes, their rankings generally align with each other.

Based on the results obtained from the present work, the following issues are suggested for further developments of the DSS for the selection of drying technologies:

- Including the emerging drying technologies in the database. Several emerging technologies such as dielectric drying, infrared drying, combined drying, and super heated-steam drying are still excluded in the DSS due to the fact that they are not commonly found in the practice of food industry, and that the selection of such technologies demands great time and effort which go beyond the confines of this study.
- Quantitatively evaluating the performances of drying technologies with respect to economic and social criteria. They are currently qualitatively evaluated that may be underestimated in the overall final decision.
- Computing the DSS on a more professional software platform to make it become more functional and user-friendly, for example Matlab.

As a final remark, it is worth to stress that the proposed decision support approach can be extended to many other thermal energy intensive processes, for example boiling, cooking, pasteurization. Therefore the development of decision support systems for the selection of such processes can be desirable in future applications.

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# Annex

## Annex 1. Configuration of drying technologies

### Annex 1-1. List of drying technologies

| No. | Technology ID | Drying technology alternative | Processing subsystem | Heating subsystem | Heat recovery subsystem |
|---|---|---|---|---|---|
| 1 | A001 | Contact cabinet dryer - Boiler/heater-non renewable energy - No heat recover | PS01 | HS01 | RS01 |
| 2 | A004 | Contact cabinet dryer - Boiler-renewable energy - No heat recovery | PS01 | HS02 | RS01 |
| 3 | A007 | Contact cabinet dryer - Boiler-mixed type - No heat recovery | PS01 | HS03 | RS01 |
| 4 | A019 | Contact tunnel dryer - Boiler/heater-non renewable energy - No heat recovery | PS02 | HS01 | RS01 |
| 5 | A022 | Contact tunnel dryer - Boiler-renewable energy - No heat recovery | PS02 | HS02 | RS01 |
| 6 | A025 | Contact tunnel dryer - Boiler-mixed type - No heat recovery | PS02 | HS03 | RS01 |
| 7 | A037 | Plate dryer - Boiler/heater-non renewable energy - No heat recovery | PS03 | HS01 | RS01 |
| 8 | A040 | Plate dryer - Boiler-renewable energy - No heat recovery | PS03 | HS02 | RS01 |
| 9 | A043 | Plate dryer - Boiler-mixed type - No heat recovery | PS03 | HS03 | RS01 |
| 10 | A055 | Contact conveyor dryers - Boiler/heater-non renewable energy - No heat reco | PS04 | HS01 | RS01 |
| 11 | A058 | Contact conveyor dryers - Boiler-renewable energy - No heat recovery | PS04 | HS02 | RS01 |
| 12 | A061 | Contact conveyor dryers - Boiler-mixed type - No heat recovery | PS04 | HS03 | RS01 |
| 13 | A073 | Rotary steam tube dryer - Boiler/heater-non renewable energy - No heat reco | PS05 | HS01 | RS01 |
| 14 | A076 | Rotary steam tube dryer - Boiler-renewable energy - No heat recovery | PS05 | HS02 | RS01 |
| 15 | A079 | Rotary steam tube dryer - Boiler-mixed type - No heat recovery | PS05 | HS03 | RS01 |
| 16 | A091 | Drum dryer - Boiler/heater-non renewable energy - No heat recovery | PS06 | HS01 | RS01 |
| 17 | A094 | Drum dryer - Boiler-renewable energy - No heat recovery | PS06 | HS02 | RS01 |
| 18 | A097 | Drum dryer - Boiler-mixed type - No heat recovery | PS06 | HS03 | RS01 |
| 19 | A109 | Direct cabinet dryer - Boiler/heater-non renewable energy - No heat recovery | PS07 | HS01 | RS01 |
| 20 | A110 | Direct cabinet dryer - Boiler/heater-non renewable energy - Exhaust air recircu | PS07 | HS01 | RS02 |
| 21 | A111 | Direct cabinet dryer - Boiler/heater-non renewable energy - Exhaust air heat e | PS07 | HS01 | RS03 |
| 22 | A112 | Direct cabinet dryer - Boiler-renewable energy - No heat recovery | PS07 | HS02 | RS01 |
| 23 | A113 | Direct cabinet dryer - Boiler-renewable energy - Exhaust air recirculation | PS07 | HS02 | RS02 |
| 24 | A114 | Direct cabinet dryer - Boiler-renewable energy - Exhaust air heat exchanger | PS07 | HS02 | RS03 |
| 25 | A115 | Direct cabinet dryer - Boiler-mixed type - No heat recovery | PS07 | HS03 | RS01 |
| 26 | A116 | Direct cabinet dryer - Boiler-mixed type - Exhaust air recirculation | PS07 | HS03 | RS02 |
| 27 | A117 | Direct cabinet dryer - Boiler-mixed type - Exhaust air heat exchanger | PS07 | HS03 | RS03 |
| 28 | A118 | Direct cabinet dryer - Solar collector - No heat recovery | PS07 | HS04 | RS01 |
| 29 | A121 | Direct cabinet dryer - Heat pump - No heat recovery | PS07 | HS05 | RS01 |
| 30 | A127 | Direct tunnel dryer - Boiler/heater-non renewable energy - No heat recovery | PS08 | HS01 | RS01 |
| 31 | A128 | Direct tunnel dryer - Boiler/heater-non renewable energy - Exhaust air recircul | PS08 | HS01 | RS02 |
| 32 | A129 | Direct tunnel dryer - Boiler/heater-non renewable energy - Exhaust air heat ex | PS08 | HS01 | RS03 |
| 33 | A130 | Direct tunnel dryer - Boiler-renewable energy - No heat recovery | PS08 | HS02 | RS01 |
| 34 | A131 | Direct tunnel dryer - Boiler-renewable energy - Exhaust air recirculation | PS08 | HS02 | RS02 |
| 35 | A132 | Direct tunnel dryer - Boiler-renewable energy - Exhaust air heat exchanger | PS08 | HS02 | RS03 |
| 36 | A133 | Direct tunnel dryer - Boiler-mixed type - No heat recovery | PS08 | HS03 | RS01 |
| 37 | A134 | Direct tunnel dryer - Boiler-mixed type - Exhaust air recirculation | PS08 | HS03 | RS02 |
| 38 | A135 | Direct tunnel dryer - Boiler-mixed type - Exhaust air heat exchanger | PS08 | HS03 | RS03 |
| 39 | A136 | Direct tunnel dryer - Solar collector - No heat recovery | PS08 | HS04 | RS01 |
| 40 | A139 | Direct tunnel dryer - Heat pump - No heat recovery | PS08 | HS05 | RS01 |
| 41 | A145 | Direct conveyor dryers - Boiler/heater-non renewable energy - No heat recove | PS09 | HS01 | RS01 |
| 42 | A146 | Direct conveyor dryers - Boiler/heater-non renewable energy - Exhaust air rec | PS09 | HS01 | RS02 |
| 43 | A147 | Direct conveyor dryers - Boiler/heater-non renewable energy - Exhaust air hea | PS09 | HS01 | RS03 |
| 44 | A148 | Direct conveyor dryers - Boiler-renewable energy - No heat recovery | PS09 | HS02 | RS01 |
| 45 | A149 | Direct conveyor dryers - Boiler-renewable energy - Exhaust air recirculation | PS09 | HS02 | RS02 |
| 46 | A150 | Direct conveyor dryers - Boiler-renewable energy - Exhaust air heat exchange | PS09 | HS02 | RS03 |
| 47 | A151 | Direct conveyor dryers - Boiler-mixed type - No heat recovery | PS09 | HS03 | RS01 |
| 48 | A152 | Direct conveyor dryers - Boiler-mixed type - Exhaust air recirculation | PS09 | HS03 | RS02 |
| 49 | A153 | Direct conveyor dryers - Boiler-mixed type - Exhaust air heat exchanger | PS09 | HS03 | RS03 |
| 50 | A154 | Direct conveyor dryers - Solar collector - No heat recovery | PS09 | HS04 | RS01 |
| 51 | A157 | Direct conveyor dryers - Heat pump - No heat recovery | PS09 | HS05 | RS01 |
| 52 | A163 | Chamber/bin dryer - Boiler/heater-non renewable energy - No heat recovery | PS10 | HS01 | RS01 |
| 53 | A164 | Chamber/bin dryer - Boiler/heater-non renewable energy - Exhaust air recircul | PS10 | HS01 | RS02 |
| 54 | A165 | Chamber/bin dryer - Boiler/heater-non renewable energy - Exhaust air heat ex | PS10 | HS01 | RS03 |
| 55 | A166 | Chamber/bin dryer - Boiler-renewable energy - No heat recovery | PS10 | HS02 | RS01 |

| No. | Technology ID | Drying technology alternative | Processing subsystem | Heating subsystem | Heat recovery subsystem |
|---|---|---|---|---|---|
| 56 | A167 | Chamber/bin dryer - Boiler-renewable energy - Exhaust air recirculation | PS10 | HS02 | RS02 |
| 57 | A168 | Chamber/bin dryer - Boiler-renewable energy - Exhaust air heat exchanger | PS10 | HS02 | RS03 |
| 58 | A169 | Chamber/bin dryer - Boiler-mixed type - No heat recovery | PS10 | HS03 | RS01 |
| 59 | A170 | Chamber/bin dryer - Boiler-mixed type - Exhaust air recirculation | PS10 | HS03 | RS02 |
| 60 | A171 | Chamber/bin dryer - Boiler-mixed type - Exhaust air heat exchanger | PS10 | HS03 | RS03 |
| 61 | A175 | Chamber/bin dryer - Heat pump - No heat recovery | PS10 | HS05 | RS01 |
| 62 | A181 | Direct rotary dryer - Boiler/heater-non renewable energy - No heat recovery | PS11 | HS01 | RS01 |
| 63 | A182 | Direct rotary dryer - Boiler/heater-non renewable energy - Exhaust air recircul | PS11 | HS01 | RS02 |
| 64 | A183 | Direct rotary dryer - Boiler/heater-non renewable energy - Exhaust air heat ex | PS11 | HS01 | RS03 |
| 65 | A184 | Direct rotary dryer - Boiler-renewable energy - No heat recovery | PS11 | HS02 | RS01 |
| 66 | A185 | Direct rotary dryer - Boiler-renewable energy - Exhaust air recirculation | PS11 | HS02 | RS02 |
| 67 | A186 | Direct rotary dryer - Boiler-renewable energy - Exhaust air heat exchanger | PS11 | HS02 | RS03 |
| 68 | A187 | Direct rotary dryer - Boiler-mixed type - No heat recovery | PS11 | HS03 | RS01 |
| 69 | A188 | Direct rotary dryer - Boiler-mixed type - Exhaust air recirculation | PS11 | HS03 | RS02 |
| 70 | A189 | Direct rotary dryer - Boiler-mixed type - Exhaust air heat exchanger | PS11 | HS03 | RS03 |
| 71 | A193 | Direct rotary dryer - Heat pump - No heat recovery | PS11 | HS05 | RS01 |
| 72 | A199 | Fluidized bed dryer - Boiler/heater-non renewable energy - No heat recovery | PS12 | HS01 | RS01 |
| 73 | A200 | Fluidized bed dryer - Boiler/heater-non renewable energy - Exhaust air recircu | PS12 | HS01 | RS02 |
| 74 | A201 | Fluidized bed dryer - Boiler/heater-non renewable energy - Exhaust air heat ex | PS12 | HS01 | RS03 |
| 75 | A202 | Fluidized bed dryer - Boiler-renewable energy - No heat recovery | PS12 | HS02 | RS01 |
| 76 | A203 | Fluidized bed dryer - Boiler-renewable energy - Exhaust air recirculation | PS12 | HS02 | RS02 |
| 77 | A204 | Fluidized bed dryer - Boiler-renewable energy - Exhaust air heat exchanger | PS12 | HS02 | RS03 |
| 78 | A205 | Fluidized bed dryer - Boiler-mixed type - No heat recovery | PS12 | HS03 | RS01 |
| 79 | A206 | Fluidized bed dryer - Boiler-mixed type - Exhaust air recirculation | PS12 | HS03 | RS02 |
| 80 | A207 | Fluidized bed dryer - Boiler-mixed type - Exhaust air heat exchanger | PS12 | HS03 | RS03 |
| 81 | A211 | Fluidized bed dryer - Heat pump - No heat recovery | PS12 | HS05 | RS01 |
| 82 | A217 | Spouted bed dryer - Boiler/heater-non renewable energy - No heat recovery | PS13 | HS01 | RS01 |
| 83 | A218 | Spouted bed dryer - Boiler/heater-non renewable energy - Exhaust air recircul | PS13 | HS01 | RS02 |
| 84 | A219 | Spouted bed dryer - Boiler/heater-non renewable energy - Exhaust air heat ex | PS13 | HS01 | RS03 |
| 85 | A220 | Spouted bed dryer - Boiler-renewable energy - No heat recovery | PS13 | HS02 | RS01 |
| 86 | A221 | Spouted bed dryer - Boiler-renewable energy - Exhaust air recirculation | PS13 | HS02 | RS02 |
| 87 | A222 | Spouted bed dryer - Boiler-renewable energy - Exhaust air heat exchanger | PS13 | HS02 | RS03 |
| 88 | A223 | Spouted bed dryer - Boiler-mixed type - No heat recovery | PS13 | HS03 | RS01 |
| 89 | A224 | Spouted bed dryer - Boiler-mixed type - Exhaust air recirculation | PS13 | HS03 | RS02 |
| 90 | A225 | Spouted bed dryer - Boiler-mixed type - Exhaust air heat exchanger | PS13 | HS03 | RS03 |
| 91 | A235 | Spray dryer - Boiler/heater-non renewable energy - No heat recovery | PS14 | HS01 | RS01 |
| 92 | A236 | Spray dryer - Boiler/heater-non renewable energy - Exhaust air recirculation | PS14 | HS01 | RS02 |
| 93 | A237 | Spray dryer - Boiler/heater-non renewable energy - Exhaust air heat exchange | PS14 | HS01 | RS03 |
| 94 | A238 | Spray dryer - Boiler-renewable energy - No heat recovery | PS14 | HS02 | RS01 |
| 95 | A239 | Spray dryer - Boiler-renewable energy - Exhaust air recirculation | PS14 | HS02 | RS02 |
| 96 | A240 | Spray dryer - Boiler-renewable energy - Exhaust air heat exchanger | PS14 | HS02 | RS03 |
| 97 | A241 | Spray dryer - Boiler-mixed type - No heat recovery | PS14 | HS03 | RS01 |
| 98 | A242 | Spray dryer - Boiler-mixed type - Exhaust air recirculation | PS14 | HS03 | RS02 |
| 99 | A243 | Spray dryer - Boiler-mixed type - Exhaust air heat exchanger | PS14 | HS03 | RS03 |
| 100 | A253 | Pneumatic flash dryer - Boiler/heater-non renewable energy - No heat recover | PS15 | HS01 | RS01 |
| 101 | A254 | Pneumatic flash dryer - Boiler/heater-non renewable energy - Exhaust air reci | PS15 | HS01 | RS02 |
| 102 | A255 | Pneumatic flash dryer - Boiler/heater-non renewable energy - Exhaust air heat | PS15 | HS01 | RS03 |
| 103 | A256 | Pneumatic flash dryer - Boiler-renewable energy - No heat recovery | PS15 | HS02 | RS01 |
| 104 | A257 | Pneumatic flash dryer - Boiler-renewable energy - Exhaust air recirculation | PS15 | HS02 | RS02 |
| 105 | A258 | Pneumatic flash dryer - Boiler-renewable energy - Exhaust air heat exchanger | PS15 | HS02 | RS03 |
| 106 | A259 | Pneumatic flash dryer - Boiler-mixed type - No heat recovery | PS15 | HS03 | RS01 |
| 107 | A260 | Pneumatic flash dryer - Boiler-mixed type - Exhaust air recirculation | PS15 | HS03 | RS02 |
| 108 | A261 | Pneumatic flash dryer - Boiler-mixed type - Exhaust air heat exchanger | PS15 | HS03 | RS03 |
| 109 | A286 | Freeze dryer - Refrigeration plant - No heat recovery | PS16 | HS06 | RS01 |

## Annex 2. Specification of the subsystems

### Annex 2-1. Specification of the processing subsystem

| ID | Technology | P1 | | P2 | | P3 | | | P4 | | | | | | | P5 | | | P6 | | | | | P7 | | | | | | P8 | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | | P11 | P12 | P21 | P22 | P31 | P32 | P33 | P41 | P42 | P43 | P44 | P45 | P46 | P47 | P51 | P52 | P53 | P61 | P62 | P63 | P64 | P65 | P71 | P72 | P73 | P74 | P75 | P76 | P81 | P82 | P83 |
| PS01 | Contact cabinet dryer | X | - | - | X | - | X | - | - | X | - | - | - | - | - | X | - | - | X | - | - | - | - | - | - | - | X | X | - | X | X | - |
| PS02 | Contact tunnel dryer | X | X | - | X | - | X | - | - | X | - | - | - | - | - | X | X | - | X | X | X | X | - | - | - | - | X | X | - | - | X | - |
| PS03 | Plate dryer | - | X | - | X | - | X | - | - | X | - | - | - | - | - | - | - | - | X | - | - | - | - | - | - | - | - | - | - | X | X | - |
| PS04 | Contact conveyor dryers | - | X | - | X | - | X | - | - | X | - | - | - | - | - | X | X | - | - | X | X | - | X | - | - | - | X | - | - | X | X | - |
| PS05 | Rotary steam tube dryer | - | X | - | X | - | X | - | - | X | - | - | - | - | - | X | X | - | X | X | X | - | - | - | - | - | X | - | - | - | X | - |
| PS06 | Drum dryer | - | X | - | X | - | X | - | - | X | - | - | - | - | - | - | X | - | X | - | - | - | - | - | X | - | - | - | - | - | X | - |
| PS07 | Direct cabinet dryer | X | - | X | - | X | - | X | X | - | X | - | - | - | - | X | - | - | X | - | - | - | - | - | - | - | X | X | - | X | X | - |
| PS08 | Direct tunnel dryer | X | X | X | - | X | - | X | X | - | X | - | - | - | - | X | X | - | X | X | X | X | - | - | - | - | X | X | - | - | X | - |
| PS09 | Direct conveyor dryers | - | X | X | - | X | - | - | X | - | - | - | - | - | - | X | X | - | - | X | X | - | X | - | - | - | X | - | - | X | X | - |
| PS10 | Chamber/bin dryer | X | - | X | - | X | - | X | X | - | X | - | - | - | - | X | - | - | X | - | - | - | - | - | - | - | - | X | X | - | X | - |
| PS11 | Direct rotary dryer | - | X | - | X | - | X | - | - | X | - | - | - | - | - | X | X | - | X | X | X | - | - | - | - | - | X | - | - | - | X | - |
| PS12 | Fluidized bed dryer | X | X | X | - | X | - | - | X | - | - | - | - | - | - | X | X | - | - | - | - | X | - | - | - | - | X | - | - | - | X | - |
| PS13 | Spouted bed dryer | - | X | X | - | X | - | - | X | - | - | - | - | - | - | X | - | 0 | - | - | - | X | - | - | - | - | X | - | - | - | X | - |
| PS14 | Spray dryer | - | X | X | - | X | - | - | X | - | - | - | - | - | - | - | X | - | - | X | X | X | - | - | X | - | - | - | - | - | X | - |
| PS15 | Pneumatic flash dryer | - | X | X | - | X | - | - | X | - | - | - | - | - | - | X | - | - | - | - | - | X | - | X | - | - | - | - | - | - | X | - |
| PS16 | Freeze dryer | - | X | - | X | - | X | - | - | X | - | - | - | - | - | - | - | X | - | - | - | X | - | - | - | - | - | - | - | X | - | - |

### Annex 2-2. Specification of the heating subsystem

| ID | Technology | H1 | | | H2 | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|
| | | H11 | H12 | H13 | H21 | H22 | H23 | H24 | H25 | H26 |
| HS01 | Boiler/heater-non renewable | X | X | - | X | - | - | - | - | - |
| HS02 | Boiler-renewable energy | X | X | - | - | X | - | - | - | - |
| HS03 | Boiler-mixed type | X | X | - | - | - | X | X | - | - |
| HS04 | Solar collector | - | - | X | - | - | - | - | - | X |
| HS05 | Heat pump | X | - | - | - | - | - | - | X | - |
| HS06 | Refrigeration plant | - | X | - | - | - | - | - | X | - |

### Annex 2-3. Specification of the heat recovery subsystem

| ID | Technology | R1 | | |
|---|---|---|---|---|
| | | R11 | R12 | R13 |
| RS01 | No heat recovery | X | - | - |
| RS02 | Exhaust air recirculation | - | X | - |
| RS03 | Exhaust air heat exchanger | - | - | X |

## Annex 3. Selection of dessicated coconut dryers

Annex 3-1. Literature values of drying process specification

| *Dryer type* | *Product* | *Moisture content of solid* | | *Mass flow rate* | *Air velocity* | *Air temperature* | | *Drying time* | *Reference* |
|---|---|---|---|---|---|---|---|---|---|
| | | *Inlet* | *Outlet* | | | *Inlet* | *Outlet* | | |
| **Tray cabinet dryers** | | | | | | | | | |
| Batch type cabinet dryer | Potato chips | 90% | 8 - 10% | 5 - 7 $kg/m^2$ | 1.5 - 1.7 m/s | 55 - 65°C | - | 180 - 240 min | Das et al. (2001) |
| Batch type cabinet dryer | Cauliflower, cabbages, onions | 90 - 93% | 7.5 - 8% | - | 0.33 $m^3/s$ | 55 - 65°C | - | 11 - 14 h | Singh (1994) |
| Batch type cabinet dryer | Red pepper slices | - | 10% | - | 1.5 m/s | 55 - 70°C | - | 5.33 h | Akpinar (2004) |
| Batch type cabinet dryer | Fruit of coroba palm | - | - | - | 0.8 - 1.2 m/s | 71 - 93°C | - | 150 min | Corzo et al. (2008) |
| Batch type cabinet dryer | Herb | 59.7 - 80.1% | 14.31 - 14.90% | 84 - 145 kg/batch | - | 46 ± 4°C | - | 6 - 9 h | Soysal and Oztekin (2001) |

| Dryer type | Product | Moisture content of solid | | Mass flow rate | Air velocity | Air temperature | | Drying time | Reference |
|---|---|---|---|---|---|---|---|---|---|
| | | Inlet | Outlet | | | Inlet | Outlet | | |
| Cabinet dryer | Strawberry slices | 8.61% | 0.01% | - | 0.5 - 1.5 m/s | 60 - 85°C | - | - | Akpinar (2007) |
| **Tunnel dryers** | | | | | | | | | |
| Tunnel dryer | - | - | - | - | - | 71°C | 43°C | 18 h | Ridley (1921) |
| Tunnel dryer | Prune | 69.4 - 71.1% | 17.2 - 21.2% | - | - | - | - | 18 - 20 h | Thompson et al. (1981) |
| **Conveyor dryers** | | | | | | | | | |
| Continuous band dryer | Carrot slices | 89.3% | - | $2.98.10^{-4}$ - $4.16.10^{-4}$ kg/s | 0.6 - 1.8 kg/s | 50 - 70°C | - | - | Aghbashlo et al. (2009) |
| **Fluid bed dryers** | | | | | | | | | |
| FBD | white button mushroom slice | 80.9% | 15 - 16% | - | 2.75 m/s | 35 - 50°C | - | 180 - 360 min | Biaobrzewski et al (2008) |

| *Dryer type* | *Product* | *Moisture content of solid* | | *Mass flow rate* | *Air velocity* | *Air temperature* | | *Drying time* | *Reference* |
|---|---|---|---|---|---|---|---|---|---|
| | | *Inlet* | *Outlet* | | | *Inlet* | *Outlet* | | |
| Batch FBD | Corn | 24.6 - 32.4% | - | - | 2.2 m/s | 50 - 63°C | - | - | Syahrul et al. (2002) |
| Batch FBD | Chopped coconut pieces | 60% | 2% | 50 kg/batch | 3.8 - 5.9 m/s | 65 - 120°C | - | - | Niamnuy and Devahastin (2005) |
| Batch FBD | grape, apricot, peach | 81 - 88% | 12 - 15% | - | - | 92 - 100°C | 72 - 78°C | 30 - 193 min | Bauman et al.(2005) |
| Batch FBD | Artemia cysts | 50 - 55% | <5% | 21.5 kg/batch | - | 40 - 90°C | 40 - 50°C | 135 - 595 min | Bosteels et al. (1996) |
| Batch FBD | Rice | 20% | 13% | - | 500 lit/min | 140°C | - | 2 h | Nimmol and Devahastin (2010) |
| Continuous FBD | Mustard | 45% | 8% | 0.0023 - 0.0042 kg/s | 1.6 | 65 - 105°C | - | 32 - 192 min | Nimmol and Devahastin (2010) |
| Continuous FBD | Chilies | 73% | 6.53 - 14.72% | - | 4 - 6 m/s | 50 - 100°C | - | 2.25 - 22.5 h | Charmongkolpradit et al. (2010) |
| Semi FBD | Rice | 17.7% | 11% | - | - | 40 - 80°C | - | 40 - 280 min | Taghaza et al. (2007) |
| Pulsed FBD | Paddy | 33% | 25.3% | - | - | 145°C | 77°C | - | Prachayawarakorn |

| *Dryer type* | *Product* | *Moisture content of solid* | | *Mass flow rate* | *Air velocity* | *Air temperature* | | *Drying time* | *Reference* |
|---|---|---|---|---|---|---|---|---|---|
| | | *Inlet* | *Outlet* | | | *Inlet* | *Outlet* | | |
| | | | | | | | | | et al. (2005) |
| FBD | Paddy | 33% | 25.3% | - | - | 144 - 155°C | 77°C | - | Prachayawarakorn et al. (2005) |
| Vibro-FBD | Paddy | 24 - 28% | 20.7 - 23.7% | 4,821 kg/h | 1.7 $m^3$/s | 125 - 140°C | 62 - 64°C | 1 min | Wetchacama et al. (2000) |
| Rectangular fluid bed | - | 82% | - | - | - | 80°C | - | 120 min | Thianpong et al. (2010) |
| **Pneumatic (flash) dryers** | | | | | | | | | |
| Single-pass flash dryer | Potato starch, corn starch, fiber and corn steep liquor | - | 20% | 4,000 - 5,000 kg/h | - | 140 - 160°C | 43 - 133°C | - | Bahu (1997) |
| Ring flash dryer | corn starch | - | 3 - 12% | 2,000 - 10,000 kg/h | - | 160 - 230°C | 54 - 100°C | - | Bahu (1997) |

| Dryer type | Product | Moisture content of solid | | Mass flow rate | Air velocity | Air temperature | | Drying time | Reference |
|---|---|---|---|---|---|---|---|---|---|
| | | Inlet | Outlet | | | Inlet | Outlet | | |
| | Fiber, gluten and corn steep liquor | - | 12% | 2,500 kg/h | - | 400°C | 100°C | - | Bahu (1997) |
| | Fiber and corn steep liquor | - | 10% | 5,000 kg/h | - | 445°C | 115°C | - | Bahu (1997) |
| Two-stage flash dryer | Corn starch | - | 2% | 2,500 kg/h | - | 210°C | 115°C | - | Bahu (1997) |
| Pneumatic dryer | - | 35 - 41% | 10 - 15% | - | - | 425°C | - | - | Prvulovic et al. (2007) |
| Pneumatic dryer | Starch | - | - | - | - | 150°C | 65°C | - | Prvulovic et al. (2007) |
| **Spray dryers** | | | | | | | | | |
| Spray dryer | Orange juice concentrate | 65% | 2.0 - 7.2% | - | - | 110 - 140°C | 48 - 69°C | - | Goula and Adamopoulos (2010) |

| Dryer type | Product | Moisture content of solid | | Mass flow rate | Air velocity | Air temperature | | Drying time | Reference |
|---|---|---|---|---|---|---|---|---|---|
| | | Inlet | Outlet | | | Inlet | Outlet | | |
| Spray dryer | Skim milk | 45 - 52% | 4% | - | - | 180 - 230°C | 80 - 95°C | - | Filkova et al. (2006), Bhandari et al. (2008) |
| | Whole milk | 40 - 50% | 2.5% | - | - | 180 - 200°C | 80 - 90°C | - | |
| | Whey, lactose | 40 - 50% | 4% | - | - | 150 - 180°C | 70 - 80°C | - | |
| | Coffee | 20 - 30% | - | - | - | 180 - 220°C | 80 - 95°C | - | |
| | Coffee (instant) | 75 - 85% | 3 - 3,5% | - | - | 270°C | 110°C | - | |
| | Maltodexin | 50 - 80% | - | - | - | 150 - 300°C | 80 - 100°C | - | |
| | Fruit juice, honey | 40 - 50% | - | - | - | 150 - 160°C | 65 - 80°C | - | |
| | Bacterial cultures | 20 - 30% | - | - | - | 140 - 150°C | 55 - 60°C | - | |
| | Cheese | 40 - 50% | - | - | - | 150 - 180°C | 60 - 75°C | - | |

| *Dryer type* | *Product* | *Moisture content of solid* | | *Mass flow rate* | *Air velocity* | *Air temperature* | | *Drying time* | *Reference* |
|---|---|---|---|---|---|---|---|---|---|
| | | *Inlet* | *Outlet* | | | *Inlet* | *Outlet* | | |
| | powder | | | | | | | | |
| | Flavor powder | 40 - 50% | - | - | - | 170 - 190°C | 75 - 80°C | - | |
| | Tea (instant) | 60% | 2% | - | - | 190 - 250°C | 90 - 100°C | - | |
| | Whole eggs | 74 - 76% | 2,0 - 4,0% | - | - | 140 - 200°C | 50 - 80°C | - | |
| **Rotary dryers** | | | | | | | | | |
| Direct rotary dryer | Lettuce, vegetable leaves, fruits | 71% | 10% | - | 1 - 1.4 $m^3/s$ | 221°C | - | 21 - 30 min | Iguaz et al. (2002, 2003) |
| **Sun and solar dryers-** | | | | | | | | | |
| Double pass solar dryer | Red chilies | 90.21% | 10% | - | 648.7 $m^3/h$ | 71°C | 53 - 54°C | 32 h | Banout et al. (2011) |
| Natural convection solar dryer | - | - | - | - | 64.5 $m^3/h$ | 61°C | 44 - 49°C | 73 h | Banout et al. (2011) |

| Dryer type | Product | Moisture content of solid | | Mass flow rate | Air velocity | Air temperature | | Drying time | Reference |
|---|---|---|---|---|---|---|---|---|---|
| | | Inlet | Outlet | | | Inlet | Outlet | | |
| Open air sun drying | - | - | - | - | - | 39°C | 33 - 35°C | - | Banout et al. (2011) |
| Solar tunnel dryer | Mushroom | 89.41% | 6.14% | - | - | 55°C | - | 8 h | Bala et al. (2009) |
| Indirect Cabinet solar dryer | Orange peels | - | - | 10 kg/batch | 1.2 - 2.1 m/s | 57 - 75°C | - | - | Slama and Combarnous (2011) |
| Mixed mode solar dryer | Onion flakes | 85.5% | 6.77% | 10 kg/batch | 125 kg/h | 54°C | 52°C | 7 h | Kothari et al. (2009) |
| Forced convection solar dryer | Copra | 51.8% | 7.8 - 9.7% | 300 kg/batch | - | 43 - 63°C | - | 82 h | Mohanraj and Chandrasekar (2008) |

## Annex 4. Selection of coconut dryers

Annex 4-1. Thermodynamic parameters of the drying process of coconut

| Parameters | Notation | Unit | Value | | |
|---|---|---|---|---|---|
| GENERAL PARAMETERS | | | | | |
| **Material and product parameters** | | | | | |
| Initial moisture content of feed or | wi | kg/kg | (0.5 , 0.55 , 0.6) | | |
| Final moisture content of product | wo | kg/kg | (0.02 , 0.03 , 0.03) | | |
| Inlet temperature of feed substan | Tmi | oC | (25 , 28 , 30) | | |
| Average specific heat capacity o | cpm | kJ/kg.oC | (2.05 , 2.13 , 2.21) | | |
| Specific heat capacity of dried p | cpm-o | kJ/kg.oC | (1.36 , 1.37 , 1.39) | | |
| **Specific heat, latent heat** | | | | | |
| Specific heat capacity of feed su | cpm-i | kJ/kg.oC | (2.74 , 2.88 , 3.03) | | |
| Specific heat capacity of dry air | Cpa | kJ/kg.oC | (1 , 1 , 1) | | |
| Specific heat capacity of vapor | cpv | kJ/kg.oC | (1.86 , 1.87 , 1.88) | | |
| Specific heat of frozen water | cpwf | kJ/kg.oC | (2.1 , 2.1 , 2.1) | | |
| Latent heat of vaporization | ΔHwv | kJ/kg | (2410.2 , 2414.9 , 2422.1) | | |
| | | | | | |
| HOT AIR DRYING | | | GROUP 1 | GROUP 2 | GROUP 3 |
| **State 0 Ambient air** | | | | | |
| Ambient air temperature | Tamb | oC | (28 , 30 , 32) | (28 , 30 , 32) | (28 , 30 , 32) |
| Relative humidity of ambient air | Yabm | % | (55 , 60 , 65) | (55 , 60 , 65) | (55 , 60 , 65) |
| Ambient air pressure | Pamb | bar | (0.99 , 0.99 , 0.99) | (0.99 , 0.99 , 0.99) | (0.99 , 0.99 , 0.99) |
| Enthalpy of air | ho | J/kg dry air | (60.57 , 70.19 , 81.27) | (60.57 , 70.19 , 81.27) | (60.57 , 70.19 , 81.27) |
| humidity ratio | y0 | g/kg dry air | (0.01 , 0.02 , 0.02) | (0.01 , 0.02 , 0.02) | (0.01 , 0.02 , 0.02) |
| **State 1 Inlet drying air (heated air)** | | | | | |
| Temperature | T1 | oC | (80 , 90 , 100) | (100 , 110 , 120) | (140 , 150 , 160) |
| Humidity ratio | y1 | g/kg dry air | (0.01 , 0.02 , 0.02) | (0.01 , 0.02 , 0.02) | (0.01 , 0.02 , 0.02) |
| Enthalpy of air | h1 | J/kg dry air | (113.85 , 132.02 , 151.81) | (134.34 , 152.63 , 172.55) | (175.33 , 193.85 , 214.04) |
| Saturation vapour pressure | Ps1 | bar | (0.47 , 0.69 , 1) | (1 , 1.41 , 1.96) | (3.59 , 4.74 , 6.17) |
| Relative humidity | Y1 | % | (0.02 , 0.04 , 0.07) | (0.01 , 0.02 , 0.03) | (0 , 0.01 , 0.01) |
| **State 2 Outlet drying air (exhaust air)** | | | | | |
| Enthalpy of air | h2 | J/kg dry air | (113.85 , 132.02 , 151.81) | (134.34 , 152.63 , 172.55) | (175.33 , 193.85 , 214.04) |
| Dewpoint temperature | Tdp2 | oC | (29 , 32 , 35.5) | (33 , 37 , 45.5) | (39 , 42.5 , 48.5) |
| Temperature | T2 | oC | (39 , 42 , 45.5) | (43 , 47 , 55.5) | (49 , 52.5 , 58.5) |
| Saturation vapour pressure | Ps2 | bar | (0.07 , 0.08 , 0.1) | (0.09 , 0.11 , 0.16) | (0.12 , 0.14 , 0.18) |
| Humidity ratio | y2 | g/kg dry air | (0.03 , 0.04 , 0.04) | (0.04 , 0.04 , 0.05) | (0.05 , 0.06 , 0.06) |
| Relative humidity | Y2 | % | (0.46 , 0.67 , 0.93) | (0.34 , 0.6 , 0.82) | (0.4 , 0.6 , 0.78) |
| | | | | | |
| CONTACT DRYING | | | GROUP 1 | GROUP 2 | GROUP 3 |
| Drying temperature | Td | oC | (60 , 65 , 70) | (40 , 50 , 60) | (60 , 70 , 80) |
| | | | | | |
| HEAT PUMP DRYING | | | | | |
| **State 1** | | | | | |
| Temperature | Ta1 | oC | (10 , 12 , 15) | | |
| Relative humidity | Y1 | % | (1 , 1 , 1) | | |
| Saturated vapor pressure | Ps1 | Bar | (0.01 , 0.01 , 0.02) | | |
| Ambient air pressure | B | bar | (0.99 , 0.99 , 0.99) | | |
| Humidity ratio | y1 | kg/kg | (0.01 , 0.01 , 0.01) | | |
| Enthalpy | h1 | kJ/kg | (29.62 , 34.48 , 42.46) | | |
| **State 2** | | | | | |
| Temperature | Ta2 | oC | (50 , 55 , 60) | | |
| Relative humidity | y2 | kg/kg | (0.01 , 0.01 , 0.01) | | |
| Enthalpy | h2 | kJ/kg | (70.36 , 78.36 , 88.54) | | |
| **State 3** | | | | | |
| Enthalpy | h3 | kJ/kg | (70.36 , 78.36 , 88.54) | | |
| Temperature | Ta3 | oC | (30 , 32 , 35) | | |
| Humidity ratio | y3 | kg/kg | (0.02 , 0.02 , 0.02) | | |
| | | | | | |
| FREEZE DRYING | | | | | |
| **Temperature of freeze drying process** | | | | | |
| Freezing temperature of water | Twf | oC | (-2 , -1 , 0) | | |
| Freeze drying temperature of wa | Twfd | oC | (-40 , -30 , -20) | | |
| **Specific heat, latent heat** | | | | | |
| Latent heat of water freezing | ΔHwf | kJ/kg | (355 , 355 , 355) | | |
| Latent heat of water sublimation | ΔHws | kJ/kg | (2840 , 2840 , 2840) | | |
| Latent heat of water condensatio | ΔHwc | kJ/kg | (2840 , 2840 , 2840) | | |
| Latent heat of water melting | ΔHwm | kJ/kg | (334 , 334 , 334) | | |

## Annex 4-2. Justification of the selected subsystem technologies

| PROCESSING SUBSYSTEM | | SUB-CRITERIA | | | | | | |
|---|---|---|---|---|---|---|---|---|
| ID | Technology | $C_{11}$ | $C_{12}$ | $C_{21}$ | $C_{22}$ | $C_{31}$ | $C_{32}$ | $C_{33}$ |
| PS02 | Contact tunnel dryer | (2465.4 , 2508.67 , 2556.05) | (35 , 47.5 , 60) | (0.33 , 1 , 3) | (0.2 , 0.33 , 1) | (0.2 , 0.33 , 1) | (0.2 , 0.33 , 1) | (0.2 , 0.33 , 1) |
| PS04 | Contact conveyor dryers | (2465.4 , 2508.67 , 2556.05) | (35 , 47.5 , 60) | (0.33 , 1 , 3) | (0.33 , 1 , 3) | (0.33 , 1 , 3) | (0.2 , 0.33 , 1) | (0.33 , 1 , 3) |
| PS05 | Rotary steam tube dryer | (2401.7 , 2478.92 , 2560.25) | (75 , 82.5 , 90) | (1 , 3 , 5) | (1 , 3 , 5) | (0.33 , 1 , 3) | (0.33 , 1 , 3) | (1 , 3 , 5) |
| PS08 | Direct tunnel dryer | (1117.08 , 3116.91 , 6849.63) | (35 , 37.5 , 40) | (0.2 , 0.33 , 1) | (0.2 , 0.33 , 1) | (0.2 , 0.33 , 1) | (0.33 , 1 , 3) | (0.33 , 1 , 3) |
| PS09 | Direct conveyor dryers | (1117.08 , 3116.91 , 6849.63) | (35 , 47.5 , 60) | (0.2 , 0.33 , 1) | (0.33 , 1 , 3) | (0.33 , 1 , 3) | (0.33 , 1 , 3) | (0.33 , 1 , 3) |
| PS11 | Direct rotary dryer | (1603.23 , 3178.27 , 5423.7) | (40 , 55 , 70) | (0.33 , 1 , 3) | (1 , 3 , 5) | (0.33 , 1 , 3) | (1 , 3 , 5) | (3 , 5 , 5) |
| PS12 | Fluidized bed dryer | (1603.23 , 3178.27 , 5423.7) | (40 , 60 , 80) | (0.33 , 1 , 3) | (1 , 3 , 5) | (0.33 , 1 , 3) | (1 , 3 , 5) | (0.33 , 1 , 3) |

| HEATING SUBSYSTEM | | SUB-CRITERIA | | | | | | |
|---|---|---|---|---|---|---|---|---|
| ID | Technology | $C_{12}$ | $C_{14}$ | $C_{21}$ | $C_{22}$ | $C_{31}$ | $C_{32}$ | $C_{33}$ |
| HS01 | Boiler/heater-non renewable en | (70 , 77.5 , 85) | (0 , 0 , 0) | (0.33 , 1 , 3) | (0.33 , 1 , 3) | (0.33 , 1 , 3) | (0.33 , 1 , 3) | (0.33 , 1 , 3) |
| HS02 | Boiler-renewable energy | (70 , 72.5 , 75) | (100 , 100 , 100) | (0.33 , 1 , 3) | (0.33 , 1 , 3) | (0.33 , 1 , 3) | (0.33 , 1 , 3) | (0.33 , 1 , 3) |
| HS03 | Boiler-mixed type | (70 , 75 , 80) | (30 , 50 , 70) | (0.33 , 1 , 3) | (0.33 , 1 , 3) | (0.33 , 1 , 3) | (0.33 , 1 , 3) | (0.2 , 0.33 , 1) |
| HS04 | Solar collector | (40 , 50 , 60) | (100 , 100 , 100) | (1 , 3 , 5) | (1 , 3 , 5) | (0.2 , 0.33 , 1) | (0.2 , 0.33 , 1) | (0.2 , 0.33 , 1) |
| HS05 | Heat pump | (90 , 95 , 100) | (0 , 0 , 0) | (0.2 , 0.33 , 1) | (0.2 , 0.33 , 1) | (1 , 3 , 5) | (0.2 , 0.33 , 1) | (0.2 , 0.33 , 1) |

| HEAT RECOVERY SUBSYSTEM | | SUB-CRITERIA | | | | | |
|---|---|---|---|---|---|---|---|
| ID | Technology | $C_{13}$ | $C_{21}$ | $C_{22}$ | $C_{31}$ | $C_{32}$ | $C_{33}$ |
| RS01 | No heat recovery | (0 , 0 , 0) | (0.2 , 0.2 , 0.33) | (0.2 , 0.2 , 0.33) | (1 , 3 , 5) | (0.2 , 0.33 , 1) | (1 , 3 , 5) |
| RS02 | Exhaust air recirculation | (15 , 32.5 , 50) | (0.2 , 0.33 , 1) | (0.33 , 1 , 3) | (0.2 , 0.33 , 1) | (1 , 3 , 5) | (0.33 , 1 , 3) |
| RS03 | Exhaust air heat exchanger | (10 , 20 , 30) | (1 , 3 , 5) | (1 , 3 , 5) | (1 , 3 , 5) | (0.2 , 0.33 , 1) | (0.2 , 0.33 , 1) |

## Annex 4-3. Normalization data - aggregated normalization method

| PROCESSING SUBSYSTEM | | SUB-CRITERIA | | | | | | |
|---|---|---|---|---|---|---|---|---|
| ID | Technology | $C_{11}$ | $C_{12}$ | $C_{21}$ | $C_{22}$ | $C_{31}$ | $C_{32}$ | $C_{33}$ |
| PS02 | Contact tunnel dryer | (-4.67 , -0.58 , -0.1) | (0.21 , 1.76 , 9.49) | (-8.66 , -0.67 , -0.07) | (-3.36 , -0.25 , -0.04) | (0.04 , 0.74 , 18.42) | (-5.09 , -0.14 , -0.01) | (0.01 , 0.11 , 3.13) |
| PS04 | Contact conveyor dryers | (-4.67 , -0.58 , -0.1) | (0.21 , 1.76 , 9.49) | (-8.66 , -0.67 , -0.07) | (-10.08 , -0.76 , -0.07) | (0.06 , 2.22 , 55.27) | (-5.09 , -0.14 , -0.01) | (0.02 , 0.34 , 9.38) |
| PS05 | Rotary steam tube dryer | (-4.68 , -0.58 , -0.1) | (0.46 , 3.06 , 14.24) | (-14.43 , -2.01 , -0.21) | (-16.8 , -2.28 , -0.22) | (0.06 , 2.22 , 55.27) | (-15.27 , -0.43 , -0.02) | (0.07 , 1.02 , 15.64) |
| PS08 | Direct tunnel dryer | (-12.51 , -0.72 , -0.05) | (0.21 , 1.39 , 6.33) | (-2.89 , -0.22 , -0.04) | (-3.36 , -0.25 , -0.04) | (0.04 , 0.74 , 18.42) | (-15.27 , -0.43 , -0.02) | (0.02 , 0.34 , 9.38) |
| PS09 | Direct conveyor dryers | (-12.51 , -0.72 , -0.05) | (0.21 , 1.76 , 9.49) | (-2.89 , -0.22 , -0.04) | (-10.08 , -0.76 , -0.07) | (0.06 , 2.22 , 55.27) | (-15.27 , -0.43 , -0.02) | (0.02 , 0.34 , 9.38) |
| PS11 | Direct rotary dryer | (-9.91 , -0.74 , -0.07) | (0.24 , 2.04 , 11.07) | (-8.66 , -0.67 , -0.07) | (-16.8 , -2.28 , -0.22) | (0.06 , 2.22 , 55.27) | (-25.45 , -1.3 , -0.07) | (0.2 , 1.7 , 15.64) |
| PS12 | Fluidized bed dryer | (-9.91 , -0.74 , -0.07) | (0.24 , 2.23 , 12.66) | (-8.66 , -0.67 , -0.07) | (-16.8 , -2.28 , -0.22) | (0.06 , 2.22 , 55.27) | (-25.45 , -1.3 , -0.07) | (0.02 , 0.34 , 9.38) |
| HEATING SUBSYSTEM | | SUB-CRITERIA | | | | | | |
| ID | Technology | $C_{12}$ | $C_{14}$ | $C_{21}$ | $C_{22}$ | $C_{31}$ | $C_{32}$ | $C_{33}$ |
| HS01 | Boiler/heater-non renewable en | (0.35 , 2.09 , 8.33) | (0 , 0 , 0) | (-7.68 , -0.58 , -0.06) | (-13.31 , -1 , -0.08) | (0.05 , 1.42 , 37.09) | (-26.49 , -0.82 , -0.03) | (0.04 , 1 , 29.28) |
| HS02 | Boiler-renewable energy | (0.35 , 1.96 , 7.35) | (0.35 , 1.33 , 7.25) | (-7.68 , -0.58 , -0.06) | (-13.31 , -1 , -0.08) | (0.05 , 1.42 , 37.09) | (-26.49 , -0.82 , -0.03) | (0.04 , 1 , 29.28) |
| HS03 | Boiler-mixed type | (0.35 , 2.03 , 7.84) | (0.1 , 0.67 , 5.07) | (-7.68 , -0.58 , -0.06) | (-13.31 , -1 , -0.08) | (0.05 , 1.42 , 37.09) | (-26.49 , -0.82 , -0.03) | (0.02 , 0.33 , 9.76) |
| HS04 | Solar collector | (0.2 , 1.35 , 5.88) | (0.35 , 1.33 , 7.25) | (-12.81 , -1.73 , -0.19) | (-22.18 , -3 , -0.24) | (0.03 , 0.47 , 12.36) | (-8.83 , -0.27 , -0.02) | (0.02 , 0.33 , 9.76) |
| HS05 | Heat pump | (0.45 , 2.57 , 9.8) | (0 , 0 , 0) | (-2.56 , -0.19 , -0.04) | (-4.44 , -0.33 , -0.05) | (0.14 , 4.26 , 61.81) | (-8.83 , -0.27 , -0.02) | (0.02 , 0.33 , 9.76) |
| HEAT RECOVERY SUBSYSTEM | | SUB-CRITERIA | | | | | | |
| ID | Technology | $C_{13}$ | $C_{21}$ | $C_{22}$ | $C_{31}$ | $C_{32}$ | $C_{33}$ | |
| RS01 | No heat recovery | (0 , 0 , 0) | (-0.81 , -0.12 , -0.05) | (-1.27 , -0.18 , -0.05) | (0.12 , 2.56 , 37.09) | (-5.3 , -0.16 , -0.02) | (0.07 , 1.25 , 24.19) | |
| RS02 | Exhaust air recirculation | (0.11 , 1.24 , 20) | (-2.42 , -0.21 , -0.05) | (-11.46 , -0.91 , -0.09) | (0.02 , 0.28 , 7.42) | (-26.49 , -1.47 , -0.09) | (0.02 , 0.42 , 14.51) | |
| RS03 | Exhaust air heat exchanger | (0.07 , 0.76 , 12) | (-12.08 , -1.86 , -0.27) | (-19.1 , -2.72 , -0.26) | (0.12 , 2.56 , 37.09) | (-5.3 , -0.16 , -0.02) | (0.01 , 0.14 , 4.84) | |

## Annex 4-4. Aggregate the ratings of technology alternatives along the hierarchy - application for the selection of new facilities

| PROCESSING SUBSYSTEM | | CRITERIA | | | OBJECTIVE |
|---|---|---|---|---|---|
| ID | Technology | $C_1$ | $C_2$ | $C_3$ | O |
| PS02 | Contact tunnel dryer | (-2.23 , 0.59 , 4.7) | (-6.01 , -0.46 , -0.06) | (-1.68 , 0.24 , 7.18) | (-0.88 , 0.31 , 14.38) |
| PS04 | Contact conveyor dryers | (-2.23 , 0.59 , 4.7) | (-9.37 , -0.71 , -0.07) | (-1.67 , 0.81 , 21.55) | (-1.12 , 0.37 , 26.21) |
| PS05 | Rotary steam tube dryer | (-2.11 , 1.24 , 7.07) | (-15.62 , -2.14 , -0.22) | (-5.05 , 0.94 , 23.63) | (-1.81 , 0.5 , 32.12) |
| PS08 | Direct tunnel dryer | (-6.15 , 0.33 , 3.14) | (-3.12 , -0.24 , -0.04) | (-5.07 , 0.22 , 9.26) | (-1.48 , 0.2 , 13.29) |
| PS09 | Direct conveyor dryers | (-6.15 , 0.52 , 4.72) | (-6.48 , -0.49 , -0.06) | (-5.06 , 0.71 , 21.54) | (-1.72 , 0.35 , 26.27) |
| PS11 | Direct rotary dryer | (-4.83 , 0.65 , 5.5) | (-12.73 , -1.48 , -0.15) | (-8.4 , 0.87 , 23.61) | (-2.23 , 0.27 , 29.32) |
| PS12 | Fluidized bed dryer | (-4.83 , 0.74 , 6.3) | (-12.73 , -1.48 , -0.15) | (-8.46 , 0.42 , 21.53) | (-2.24 , 0.24 , 29.04) |
| **HEATING SUBSYSTEM** | | **CRITERIA** | | | **OBJECTIVE** |
| ID | Technology | $C_1$ | $C_2$ | $C_3$ | O |
| HS01 | Boiler/heater-non renewable energy | (0.18 , 1.05 , 4.17) | (-10.5 , -0.79 , -0.07) | (-8.8 , 0.53 , 22.11) | (-1.38 , 0.58 , 25.72) |
| HS02 | Boiler-renewable energy | (0.35 , 1.65 , 7.3) | (-10.5 , -0.79 , -0.07) | (-8.8 , 0.53 , 22.11) | (-1.36 , 0.94 , 31.4) |
| HS03 | Boiler-mixed type | (0.23 , 1.35 , 6.46) | (-10.5 , -0.79 , -0.07) | (-8.81 , 0.31 , 15.6) | (-1.38 , 0.71 , 24.51) |
| HS04 | Solar collector | (0.27 , 1.34 , 6.56) | (-17.49 , -2.37 , -0.22) | (-2.93 , 0.18 , 7.37) | (-1.45 , 0.37 , 17.8) |
| HS05 | Heat pump | (0.23 , 1.28 , 4.9) | (-3.5 , -0.26 , -0.04) | (-2.89 , 1.44 , 23.85) | (-0.43 , 1.01 , 28.51) |
| **HEAT RECOVERY SUBSYSTEM** | | **CRITERIA** | | | **OBJECTIVE** |
| ID | Technology | $C_1$ | $C_2$ | $C_3$ | O |
| RS01 | No heat recovery | (0 , 0 , 0) | (-1.04 , -0.15 , -0.05) | (-1.7 , 1.21 , 20.42) | (-0.2 , 0.21 , 16.78) |
| RS02 | Exhaust air recirculation | (0.11 , 1.24 , 20) | (-6.94 , -0.56 , -0.07) | (-8.81 , -0.26 , 7.28) | (-1.14 , 0.58 , 42.2) |
| RS03 | Exhaust air heat exchanger | (0.07 , 0.76 , 12) | (-15.59 , -2.29 , -0.27) | (-1.72 , 0.84 , 13.97) | (-1.25 , 0.17 , 33.05) |

## Annex 4-5. Defuzzification - application for the selection of new facilities

| PROCESSING SUBSYSTEM | | FUZZY RATING | DEFFUZIFICATION | | | RANKING |
|---|---|---|---|---|---|---|
| ID | Technology | $r_{PS}$ | $x_{PS}$ | $y_{PS}$ | $R_{PS}$ | |
| PS05 | Rotary steam tube dryer | (-1.81 , 0.5 , 32.12) | 10.27 | 0.344 | 10.276 | 1 |
| PS11 | Direct rotary dryer | (-2.23 , 0.27 , 29.32) | 9.119 | 0.34 | 9.126 | 2 |
| PS12 | Fluidized bed dryer | (-2.24 , 0.24 , 29.04) | 9.011 | 0.339 | 9.018 | 3 |
| PS04 | Contact conveyor dryers | (-1.12 , 0.37 , 26.21) | 8.487 | 0.343 | 8.494 | 4 |
| PS09 | Direct conveyor dryers | (-1.72 , 0.35 , 26.27) | 8.302 | 0.343 | 8.309 | 5 |
| PS02 | Contact tunnel dryer | (-0.88 , 0.31 , 14.38) | 4.604 | 0.348 | 4.618 | 6 |
| PS08 | Direct tunnel dryer | (-1.48 , 0.2 , 13.29) | 4.004 | 0.344 | 4.019 | 7 |
| **HEATING SUBSYSTEM** | | **FUZZY RATING** | **DEFFUZIFICATION** | | | **RANKING** |
| ID | Technology | $r_{HS}$ | $x_{HS}$ | $y_{HS}$ | $R_{HS}$ | |
| HS02 | Boiler-renewable energy | (-1.36 , 0.94 , 31.4) | 10.326 | 0.353 | 10.332 | 1 |
| HS05 | Heat pump | (-0.43 , 1.01 , 28.51) | 9.694 | 0.356 | 9.7 | 2 |
| HS01 | Boiler/heater-non renewable ener | (-1.38 , 0.58 , 25.72) | 8.304 | 0.348 | 8.311 | 3 |
| HS03 | Boiler-mixed type | (-1.38 , 0.71 , 24.51) | 7.949 | 0.353 | 7.957 | 4 |
| HS04 | Solar collector | (-1.45 , 0.37 , 17.8) | 5.57 | 0.348 | 5.581 | 5 |
| **HEAT RECOVERY SUBSYSTEM** | | **FUZZY RATING** | **DEFFUZIFICATION** | | | **RANKING** |
| ID | Technology | $r_{RS}$ | $x_{RS}$ | $y_{RS}$ | $R_{RS}$ | |
| RS02 | Exhaust air recirculation | (-1.14 , 0.58 , 42.2) | 13.883 | 0.342 | 13.887 | 1 |
| RS03 | Exhaust air heat exchanger | (-1.25 , 0.17 , 33.05) | 10.655 | 0.337 | 10.661 | 2 |
| RS01 | No heat recovery | (-0.2 , 0.21 , 16.78) | 5.599 | 0.342 | 5.609 | 3 |

## Annex 4-6. Normalization data - base-cased normalization method

| PROCESSING SUBSYSTEM | | SUB-CRITERIA | | | | | | |
|---|---|---|---|---|---|---|---|---|
| ID | Technology | $C_{11}$ | $C_{12}$ | $C_{21}$ | $C_{22}$ | $C_{31}$ | $C_{32}$ | $C_{33}$ |
| PSbc | Fluidized bed dryer | (-9.84 , -0.86 , -0.1) | (0.19 , 1.95 , 13.95) | (-9.37 , -0.7 , -0.07) | (-12.81 , -1.7 , -0.18) | (0.05 , 2 , 52.02) | (-18.43 , -0.51 , -0.02) | (0.02 , 0.45 , 14.45) |
| PS02 | Contact tunnel dryer | (-3.55 , -0.45 , -0.08) | (0.19 , 1.8 , 10.49) | (-9.37 , -0.7 , -0.07) | (-2.56 , -0.19 , -0.04) | (0.03 , 0.67 , 17.34) | (-6.14 , -0.17 , -0.01) | (0.01 , 0.15 , 4.82) |
| PS04 | Contact conveyor dryers | (-3.55 , -0.45 , -0.08) | (0.19 , 1.8 , 10.49) | (-9.37 , -0.7 , -0.07) | (-7.68 , -0.57 , -0.06) | (0.05 , 2 , 52.02) | (-6.14 , -0.17 , -0.01) | (0.02 , 0.45 , 14.45) |
| PS05 | Rotary steam tube dryer | (-3.56 , -0.44 , -0.08) | (0.41 , 3.13 , 15.74) | (-15.62 , -2.1 , -0.2) | (-12.81 , -1.7 , -0.18) | (0.05 , 2 , 52.02) | (-18.43 , -0.51 , -0.02) | (0.07 , 1.36 , 24.08) |
| PS08 | Direct tunnel dryer | (-9.52 , -0.56 , -0.04) | (0.19 , 1.42 , 6.99) | (-3.12 , -0.23 , -0.04) | (-2.56 , -0.19 , -0.04) | (0.03 , 0.67 , 17.34) | (-18.43 , -0.51 , -0.02) | (0.02 , 0.45 , 14.45) |
| PS09 | Direct conveyor dryers | (-9.52 , -0.56 , -0.04) | (0.19 , 1.8 , 10.49) | (-3.12 , -0.23 , -0.04) | (-7.68 , -0.57 , -0.06) | (0.05 , 2 , 52.02) | (-18.43 , -0.51 , -0.02) | (0.02 , 0.45 , 14.45) |
| PS11 | Direct rotary dryer | (-7.54 , -0.57 , -0.05) | (0.22 , 2.09 , 12.24) | (-9.37 , -0.7 , -0.07) | (-12.81 , -1.7 , -0.18) | (0.05 , 2 , 52.02) | (-30.72 , -1.53 , -0.07) | (0.21 , 2.26 , 24.08) |
| PS12 | Fluidized bed dryer | (-7.54 , -0.57 , -0.05) | (0.22 , 2.28 , 13.99) | (-9.37 , -0.7 , -0.07) | (-12.81 , -1.7 , -0.18) | (0.05 , 2 , 52.02) | (-30.72 , -1.53 , -0.07) | (0.02 , 0.45 , 14.45) |

| HEATING SUBSYSTEM | | SUB-CRITERIA | | | | | | |
|---|---|---|---|---|---|---|---|---|
| ID | Technology | $C_{12}$ | $C_{14}$ | $C_{21}$ | $C_{22}$ | $C_{31}$ | $C_{32}$ | $C_{33}$ |
| HSbc | Boiler-renewable energy | (0.13 , 1.67 , 13.52) | (0.25 , 0.94 , 4.91) | (-8.83 , -0.65 , -0.06) | (-15.29 , -1.13 , -0.08) | (0.05 , 1.6 , 42.61) | (-24.28 , -0.7 , -0.03) | (0.03 , 0.77 , 25.53) |
| HS01 | Boiler/heater-non renewable en | (0.33 , 2.5 , 12.95) | (0 , 0 , 0) | (-8.83 , -0.65 , -0.06) | (-15.29 , -1.13 , -0.08) | (0.05 , 1.6 , 42.61) | (-24.28 , -0.7 , -0.03) | (0.03 , 0.77 , 25.53) |
| HS02 | Boiler-renewable energy | (0.33 , 2.34 , 11.43) | (0.25 , 0.94 , 4.91) | (-8.83 , -0.65 , -0.06) | (-15.29 , -1.13 , -0.08) | (0.05 , 1.6 , 42.61) | (-24.28 , -0.7 , -0.03) | (0.03 , 0.77 , 25.53) |
| HS03 | Boiler-mixed type | (0.33 , 2.42 , 12.19) | (0.08 , 0.47 , 3.44) | (-8.83 , -0.65 , -0.06) | (-15.29 , -1.13 , -0.08) | (0.05 , 1.6 , 42.61) | (-24.28 , -0.7 , -0.03) | (0.02 , 0.26 , 8.51) |
| HS04 | Solar collector | (0.19 , 1.61 , 9.14) | (0.25 , 0.94 , 4.91) | (-14.71 , -1.95 , -0.19) | (-25.49 , -3.38 , -0.24) | (0.03 , 0.53 , 14.2) | (-8.09 , -0.23 , -0.02) | (0.02 , 0.26 , 8.51) |
| HS05 | Heat pump | (0.43 , 3.07 , 15.24) | (0 , 0 , 0) | (-2.94 , -0.22 , -0.04) | (-5.1 , -0.38 , -0.05) | (0.14 , 4.8 , 71.02) | (-8.09 , -0.23 , -0.02) | (0.02 , 0.26 , 8.51) |

| HEAT RECOVERY SUBSYSTEM | | SUB-CRITERIA | | | | | |
|---|---|---|---|---|---|---|---|
| ID | Technology | $C_{13}$ | $C_{21}$ | $C_{22}$ | $C_{31}$ | $C_{32}$ | $C_{33}$ |
| RSbc | No heat recovery | (0 , 0 , 0) | (-1.23 , -0.3 , -0.14) | (-2.04 , -0.48 , -0.15) | (0.1 , 2.15 , 31.76) | (-8.09 , -0.31 , -0.03) | (0.06 , 0.86 , 17.29) |
| RS01 | No heat recovery | (0 , 0 , 0) | (-1.23 , -0.3 , -0.14) | (-2.04 , -0.48 , -0.15) | (0.1 , 2.15 , 31.76) | (-8.09 , -0.31 , -0.03) | (0.06 , 0.86 , 17.29) |
| RS02 | Exhaust air recirculation | (0.11 , 1.24 , 20) | (-3.69 , -0.5 , -0.14) | (-18.32 , -2.4 , -0.25) | (0.02 , 0.24 , 6.35) | (-40.47 , -2.82 , -0.14) | (0.02 , 0.29 , 10.38) |
| RS03 | Exhaust air heat exchanger | (0.07 , 0.76 , 12) | (-18.45 , -4.52 , -0.68) | (-30.53 , -7.19 , -0.76) | (0.1 , 2.15 , 31.76) | (-8.09 , -0.31 , -0.03) | (0.01 , 0.1 , 3.46) |

Annex 4-7. Aggregate the ratings of technology alternatives along the hierarchy with reference to the base-case alternative

| PROCESSING SUBSYSTEM | | CRITERIA | | | OBJECTIVE |
|---|---|---|---|---|---|
| ID | Technology | $C_1$ | $C_2$ | $C_3$ | O |
| PSbc | Fluidized bed dryer | (-4.82 , 0.55 , 6.92) | (-11.09 , -1.2 , -0.12) | (-6.12 , 0.65 , 22.15) | (-1.95 , 0.22 , 30.7) |
| PS02 | Contact tunnel dryer | (-1.68 , 0.68 , 5.21) | (-5.97 , -0.44 , -0.05) | (-2.03 , 0.22 , 7.38) | (-0.82 , 0.36 , 15.48) |
| PS04 | Contact conveyor dryers | (-1.68 , 0.68 , 5.21) | (-8.53 , -0.63 , -0.06) | (-2.02 , 0.76 , 22.15) | (-1.01 , 0.43 , 27.64) |
| PS05 | Rotary steam tube dryer | (-1.57 , 1.34 , 7.83) | (-14.21 , -1.9 , -0.19) | (-6.1 , 0.95 , 25.36) | (-1.71 , 0.62 , 34.94) |
| PS08 | Direct tunnel dryer | (-4.66 , 0.43 , 3.48) | (-2.84 , -0.21 , -0.04) | (-6.13 , 0.2 , 10.59) | (-1.32 , 0.26 , 15) |
| PS09 | Direct conveyor dryers | (-4.66 , 0.62 , 5.23) | (-5.4 , -0.4 , -0.05) | (-6.12 , 0.65 , 22.15) | (-1.51 , 0.42 , 27.69) |
| PS11 | Direct rotary dryer | (-3.66 , 0.76 , 6.09) | (-11.09 , -1.2 , -0.12) | (-10.15 , 0.91 , 25.34) | (-2.07 , 0.4 , 31.83) |
| PS12 | Fluidized bed dryer | (-3.66 , 0.85 , 6.97) | (-11.09 , -1.2 , -0.12) | (-10.22 , 0.31 , 22.13) | (-2.08 , 0.33 , 30.77) |
| HEATING SUBSYSTEM | | CRITERIA | | | OBJECTIVE |
| ID | Technology | $C_1$ | $C_2$ | $C_3$ | O |
| HSbc | Boiler-renewable energy | (0.19 , 1.31 , 9.22) | (-12.06 , -0.89 , -0.07) | (-8.07 , 0.56 , 22.7) | (-1.44 , 0.72 , 35.36) |
| HS01 | Boiler/heater-non renewable energy | (0.17 , 1.25 , 6.48) | (-12.06 , -0.89 , -0.07) | (-8.07 , 0.56 , 22.7) | (-1.45 , 0.68 , 30.39) |
| HS02 | Boiler-renewable energy | (0.29 , 1.64 , 8.17) | (-12.06 , -0.89 , -0.07) | (-8.07 , 0.56 , 22.7) | (-1.43 , 0.92 , 33.47) |
| HS03 | Boiler-mixed type | (0.2 , 1.45 , 7.82) | (-12.06 , -0.89 , -0.07) | (-8.07 , 0.39 , 17.03) | (-1.44 , 0.77 , 28.15) |
| HS04 | Solar collector | (0.22 , 1.28 , 7.03) | (-20.1 , -2.67 , -0.22) | (-2.68 , 0.19 , 7.57) | (-1.63 , 0.27 , 18.8) |
| HS05 | Heat pump | (0.21 , 1.53 , 7.62) | (-4.02 , -0.3 , -0.04) | (-2.64 , 1.61 , 26.5) | (-0.46 , 1.18 , 35.62) |
| HEAT RECOVERY SUBSYSTEM | | CRITERIA | | | OBJECTIVE |
| ID | Technology | $C_1$ | $C_2$ | $C_3$ | O |
| RSbc | No heat recovery | (0 , 0 , 0) | (-1.63 , -0.39 , -0.14) | (-2.65 , 0.9 , 16.34) | (-0.31 , 0.1 , 13.35) |
| HS01 | Boiler/heater-non renewable energy | (0 , 0 , 0) | (-1.63 , -0.39 , -0.14) | (-2.65 , 0.9 , 16.34) | (-0.31 , 0.1 , 13.35) |
| RS02 | Exhaust air recirculation | (0.11 , 1.24 , 20) | (-11 , -1.45 , -0.19) | (-13.48 , -0.76 , 5.53) | (-1.77 , 0.3 , 40.66) |
| RS03 | Exhaust air heat exchanger | (0.07 , 0.76 , 12) | (-24.49 , -5.86 , -0.72) | (-2.66 , 0.64 , 11.73) | (-1.97 , -0.59 , 30.83) |

Annex 4-8. Defuzzification - application for changing of the used technology

| PROCESSING SUBSYSTEM | | FUZZY RATING | CRISP RATING | RANKING |
|---|---|---|---|---|
| ID | Technology | $r_{PS}$ | $R_{PS}$ | |
| PSbc | Fluidized bed dryer | (-1.95 , 0.22 , 30.7) | 9.664 | 4 |
| PS05 | Rotary steam tube dryer | (-1.71 , 0.62 , 34.94) | 11.288 | 1 |
| PS11 | Direct rotary dryer | (-2.07 , 0.4 , 31.83) | 10.058 | 2 |
| PS12 | Fluidized bed dryer | (-2.08 , 0.33 , 30.77) | 9.682 | 3 |
| PS04 | Contact conveyor dryers | (-1.01 , 0.43 , 27.64) | 9.028 | 4 |
| PS09 | Direct conveyor dryers | (-1.51 , 0.42 , 27.69) | 8.875 | 5 |
| PS02 | Contact tunnel dryer | (-0.82 , 0.36 , 15.48) | 5.017 | 6 |
| PS08 | Direct tunnel dryer | (-1.32 , 0.26 , 15) | 4.659 | 7 |
| HEATING SUBSYSTEM | | FUZZY RATING | CRISP RATING | RANKING |
| ID | Technology | $r_{HS}$ | $R_{HS}$ | |
| HSbc | Boiler-renewable energy | (-1.44 , 0.72 , 35.36) | 11.551 | 2 |
| HS05 | Heat pump | (-0.46 , 1.18 , 35.62) | 12.121 | 1 |
| HS02 | Boiler-renewable energy | (-1.43 , 0.92 , 33.47) | 10.992 | 2 |
| HS01 | Boiler/heater-non renewable ener | (-1.45 , 0.68 , 30.39) | 9.884 | 3 |
| HS03 | Boiler-mixed type | (-1.44 , 0.77 , 28.15) | 9.165 | 4 |
| HS04 | Solar collector | (-1.63 , 0.27 , 18.8) | 5.824 | 5 |
| HEAT RECOVERY SUBSYSTEM | | FUZZY RATING | CRISP RATING | RANKING |
| ID | Technology | $r_{RS}$ | $R_{RS}$ | |
| RSbc | No heat recovery | (-0.31 , 0.1 , 13.35) | 4.393 | 3 |
| RS02 | Exhaust air recirculation | (-1.77 , 0.3 , 40.66) | 13.067 | 1 |
| RS03 | Exhaust air heat exchanger | (-1.97 , -0.59 , 30.83) | 9.431 | 2 |
| RS01 | No heat recovery | (-0.31 , 0.1 , 13.35) | 4.393 | 3 |

## Annex 4-9. Ratings and rankings of the system technologies - selection of new facilities

| SYSTEM ALTERNATIVE | | SUBSYSTEM | | | FUZZY RATING | DEFFUZIFICATION | | | RANKING |
|---|---|---|---|---|---|---|---|---|---|
| ID | Technology | PS | HS | RS | $r_A$ | $x_A$ | $y_A$ | $R_A$ | |
| A185 | Direct rotary dryer - Boiler-renewabl | PS11 | HS02 | RS02 | (-0.77 , 0.5 , 74.51) | 24.74 | 0.34 | 24.75 | 1 |
| A203 | Fluidized bed dryer - Boiler-renewab | PS12 | HS02 | RS02 | (-0.78 , 0.48 , 74.15) | 24.62 | 0.34 | 24.62 | 2 |
| A186 | Direct rotary dryer - Boiler-renewabl | PS11 | HS02 | RS03 | (-0.78 , 0.45 , 72.03) | 23.9 | 0.34 | 23.9 | 3 |
| A204 | Fluidized bed dryer - Boiler-renewab | PS12 | HS02 | RS03 | (-0.78 , 0.43 , 71.67) | 23.77 | 0.34 | 23.77 | 4 |
| A076 | Rotary steam tube dryer - Boiler-ren | PS05 | HS02 | RS01 | (-0.61 , 0.6 , 71.19) | 23.73 | 0.34 | 23.73 | 5 |
| A149 | Direct conveyor dryers - Boiler-rene | PS09 | HS02 | RS02 | (-0.65 , 0.55 , 70.61) | 23.5 | 0.34 | 23.51 | 6 |
| A182 | Direct rotary dryer - Boiler/heater-no | PS11 | HS01 | RS02 | (-0.78 , 0.39 , 69.89) | 23.17 | 0.34 | 23.17 | 7 |
| A200 | Fluidized bed dryer - Boiler/heater-n | PS12 | HS01 | RS02 | (-0.78 , 0.37 , 69.52) | 23.04 | 0.34 | 23.04 | 8 |
| A188 | Direct rotary dryer - Boiler-mixed typ | PS11 | HS03 | RS02 | (-0.78 , 0.43 , 68.91) | 22.85 | 0.34 | 22.86 | 9 |
| A206 | Fluidized bed dryer - Boiler-mixed ty | PS12 | HS03 | RS02 | (-0.78 , 0.41 , 68.54) | 22.72 | 0.34 | 22.73 | 10 |
| A150 | Direct conveyor dryers - Boiler-rene | PS09 | HS02 | RS03 | (-0.66 , 0.51 , 68.13) | 22.66 | 0.34 | 22.66 | 11 |
| A184 | Direct rotary dryer - Boiler-renewabl | PS11 | HS02 | RS01 | (-0.71 , 0.46 , 67.62) | 22.45 | 0.34 | 22.46 | 12 |
| A202 | Fluidized bed dryer - Boiler-renewab | PS12 | HS02 | RS01 | (-0.71 , 0.44 , 67.25) | 22.33 | 0.34 | 22.33 | 13 |
| A183 | Direct rotary dryer - Boiler/heater-no | PS11 | HS01 | RS03 | (-0.79 , 0.35 , 67.41) | 22.32 | 0.34 | 22.33 | 14 |
| A201 | Fluidized bed dryer - Boiler/heater-n | PS12 | HS01 | RS03 | (-0.79 , 0.33 , 67.04) | 22.19 | 0.34 | 22.2 | 15 |
| A073 | Rotary steam tube dryer - Boiler/heat | PS05 | HS01 | RS01 | (-0.61 , 0.5 , 66.57) | 22.15 | 0.34 | 22.15 | 16 |
| A189 | Direct rotary dryer - Boiler-mixed typ | PS11 | HS03 | RS03 | (-0.78 , 0.39 , 66.42) | 22.01 | 0.34 | 22.01 | 17 |
| A146 | Direct conveyor dryers - Boiler/heate | PS09 | HS01 | RS02 | (-0.65 , 0.44 , 65.99) | 21.93 | 0.34 | 21.93 | 18 |
| A207 | Fluidized bed dryer - Boiler-mixed ty | PS12 | HS03 | RS03 | (-0.79 , 0.37 , 66.06) | 21.88 | 0.34 | 21.88 | 19 |
| A079 | Rotary steam tube dryer - Boiler-mix | PS05 | HS03 | RS01 | (-0.61 , 0.53 , 65.58) | 21.84 | 0.34 | 21.84 | 20 |
| A193 | Direct rotary dryer - Heat pump - No | PS11 | HS05 | RS01 | (-0.61 , 0.48 , 65.26) | 21.71 | 0.34 | 21.71 | 21 |
| A152 | Direct conveyor dryers - Boiler-mixe | PS09 | HS03 | RS02 | (-0.65 , 0.48 , 65.01) | 21.61 | 0.34 | 21.62 | 22 |
| A211 | Fluidized bed dryer - Heat pump - No | PS12 | HS05 | RS01 | (-0.61 , 0.46 , 64.9) | 21.58 | 0.34 | 21.58 | 23 |
| A058 | Contact conveyor dryers - Boiler-ren | PS04 | HS02 | RS01 | (-0.44 , 0.52 , 63.64) | 21.24 | 0.34 | 21.24 | 24 |
| A148 | Direct conveyor dryers - Boiler-rene | PS09 | HS02 | RS01 | (-0.58 , 0.51 , 63.72) | 21.21 | 0.34 | 21.22 | 25 |
| A147 | Direct conveyor dryers - Boiler/heate | PS09 | HS01 | RS03 | (-0.66 , 0.4 , 63.51) | 21.08 | 0.34 | 21.08 | 26 |
| A181 | Direct rotary dryer - Boiler/heater-no | PS11 | HS01 | RS01 | (-0.71 , 0.35 , 62.99) | 20.88 | 0.34 | 20.88 | 27 |
| A153 | Direct conveyor dryers - Boiler-mixe | PS09 | HS03 | RS03 | (-0.66 , 0.44 , 62.52) | 20.77 | 0.34 | 20.77 | 28 |
| A199 | Fluidized bed dryer - Boiler/heater-n | PS12 | HS01 | RS01 | (-0.71 , 0.33 , 62.63) | 20.75 | 0.34 | 20.75 | 29 |
| A187 | Direct rotary dryer - Boiler-mixed typ | PS11 | HS03 | RS01 | (-0.71 , 0.39 , 62.01) | 20.56 | 0.34 | 20.57 | 30 |
| A157 | Direct conveyor dryers - Heat pump | PS09 | HS05 | RS01 | (-0.48 , 0.53 , 61.36) | 20.47 | 0.34 | 20.47 | 31 |
| A205 | Fluidized bed dryer - Boiler-mixed ty | PS12 | HS03 | RS01 | (-0.71 , 0.37 , 61.64) | 20.43 | 0.34 | 20.44 | 32 |
| A055 | Contact conveyor dryers - Boiler/hea | PS04 | HS01 | RS01 | (-0.44 , 0.42 , 59.02) | 19.66 | 0.34 | 19.67 | 33 |
| A145 | Direct conveyor dryers - Boiler/heate | PS09 | HS01 | RS01 | (-0.59 , 0.4 , 59.09) | 19.64 | 0.34 | 19.64 | 34 |
| A061 | Contact conveyor dryers - Boiler-mix | PS04 | HS03 | RS01 | (-0.44 , 0.45 , 58.03) | 19.35 | 0.34 | 19.35 | 35 |
| A151 | Direct conveyor dryers - Boiler-mixe | PS09 | HS03 | RS01 | (-0.59 , 0.44 , 58.11) | 19.32 | 0.34 | 19.33 | 36 |
| A131 | Direct tunnel dryer - Boiler-renewabl | PS08 | HS02 | RS02 | (-0.59 , 0.45 , 54.01) | 17.96 | 0.34 | 17.96 | 37 |
| A154 | Direct conveyor dryers - Solar collec | PS09 | HS04 | RS01 | (-0.59 , 0.34 , 52.64) | 17.46 | 0.34 | 17.47 | 38 |
| A132 | Direct tunnel dryer - Boiler-renewabl | PS08 | HS02 | RS03 | (-0.6 , 0.41 , 51.53) | 17.11 | 0.34 | 17.12 | 39 |
| A128 | Direct tunnel dryer - Boiler/heater-no | PS08 | HS01 | RS02 | (-0.59 , 0.35 , 49.39) | 16.38 | 0.34 | 16.38 | 40 |
| A022 | Contact tunnel dryer - Boiler-renewal | PS02 | HS02 | RS01 | (-0.38 , 0.48 , 48.51) | 16.21 | 0.34 | 16.21 | 41 |
| A134 | Direct tunnel dryer - Boiler-mixed typ | PS08 | HS03 | RS02 | (-0.59 , 0.39 , 48.4) | 16.07 | 0.34 | 16.07 | 42 |
| A130 | Direct tunnel dryer - Boiler-renewabl | PS08 | HS02 | RS01 | (-0.52 , 0.41 , 47.11) | 15.67 | 0.34 | 15.67 | 43 |
| A129 | Direct tunnel dryer - Boiler/heater-no | PS08 | HS01 | RS03 | (-0.6 , 0.3 , 46.9) | 15.54 | 0.34 | 15.54 | 44 |
| A135 | Direct tunnel dryer - Boiler-mixed typ | PS08 | HS03 | RS03 | (-0.6 , 0.34 , 45.92) | 15.22 | 0.34 | 15.23 | 45 |
| A139 | Direct tunnel dryer - Heat pump - No | PS08 | HS05 | RS01 | (-0.42 , 0.43 , 44.76) | 14.92 | 0.34 | 14.93 | 46 |
| A019 | Contact tunnel dryer - Boiler/heater-r | PS02 | HS01 | RS01 | (-0.38 , 0.38 , 43.89) | 14.63 | 0.34 | 14.63 | 47 |
| A025 | Contact tunnel dryer - Boiler-mixed t | PS02 | HS03 | RS01 | (-0.38 , 0.42 , 42.9) | 14.31 | 0.34 | 14.32 | 48 |
| A127 | Direct tunnel dryer - Boiler/heater-no | PS08 | HS01 | RS01 | (-0.53 , 0.31 , 42.49) | 14.09 | 0.34 | 14.09 | 49 |
| A133 | Direct tunnel dryer - Boiler-mixed typ | PS08 | HS03 | RS01 | (-0.53 , 0.35 , 41.51) | 13.78 | 0.34 | 13.78 | 50 |
| A136 | Direct tunnel dryer - Solar collector - | PS08 | HS04 | RS01 | (-0.53 , 0.25 , 36.04) | 11.92 | 0.34 | 11.92 | 51 |

Annex 4-10. Ratings and rankings of the system technologies - technology change for existing facilities

| SYSTEM ALTERNATIVE | | SUBSYSTEM | | | FUZZY RATING | DEFFUZIFICATION | | | RANKING |
|---|---|---|---|---|---|---|---|---|---|
| ID | Technology | PS | HS | RS | $r_A$ | $x_A$ | $y_A$ | $R_A$ | |
| Abc | Fluidized bed dryer - Boiler-renewab | PSbc | HSbc | RSbc | (-0.66 , 0.35 , 71.67) | 23.79 | 0.34 | 23.79 | 18 |
| A185 | Direct rotary dryer - Boiler-renewabl | PS11 | HS02 | RS02 | (-0.79 , 0.54 , 78.99) | 26.25 | 0.34 | 26.25 | 1 |
| A203 | Fluidized bed dryer - Boiler-renewab | PS12 | HS02 | RS02 | (-0.79 , 0.5 , 77.63) | 25.78 | 0.34 | 25.78 | 2 |
| A182 | Direct rotary dryer - Boiler/heater-no | PS11 | HS01 | RS02 | (-0.79 , 0.47 , 76.49) | 25.39 | 0.34 | 25.39 | 3 |
| A186 | Direct rotary dryer - Boiler-renewabl | PS11 | HS02 | RS03 | (-0.8 , 0.45 , 76.33) | 25.32 | 0.34 | 25.33 | 4 |
| A076 | Rotary steam tube dryer - Boiler-ren | PS05 | HS02 | RS01 | (-0.6 , 0.65 , 75.55) | 25.2 | 0.34 | 25.21 | 5 |
| A200 | Fluidized bed dryer - Boiler/heater-n | PS12 | HS01 | RS02 | (-0.79 , 0.43 , 75.13) | 24.92 | 0.34 | 24.93 | 6 |
| A204 | Fluidized bed dryer - Boiler-renewab | PS12 | HS02 | RS03 | (-0.8 , 0.41 , 74.97) | 24.86 | 0.34 | 24.86 | 7 |
| A188 | Direct rotary dryer - Boiler-mixed typ | PS11 | HS03 | RS02 | (-0.79 , 0.49 , 74.66) | 24.79 | 0.34 | 24.79 | 8 |
| A149 | Direct conveyor dryers - Boiler-rene | PS09 | HS02 | RS02 | (-0.65 , 0.55 , 73.69) | 24.53 | 0.34 | 24.54 | 9 |
| A183 | Direct rotary dryer - Boiler/heater-no | PS11 | HS01 | RS03 | (-0.8 , 0.38 , 73.82) | 24.47 | 0.34 | 24.47 | 10 |
| A193 | Direct rotary dryer - Heat pump - No | PS11 | HS05 | RS01 | (-0.58 , 0.6 , 73.34) | 24.45 | 0.34 | 24.45 | 11 |
| A073 | Rotary steam tube dryer - Boiler/heat | PS05 | HS01 | RS01 | (-0.6 , 0.58 , 73.05) | 24.35 | 0.34 | 24.35 | 12 |
| A206 | Fluidized bed dryer - Boiler-mixed ty | PS12 | HS03 | RS02 | (-0.79 , 0.46 , 73.3) | 24.32 | 0.34 | 24.33 | 13 |
| A201 | Fluidized bed dryer - Boiler/heater-n | PS12 | HS01 | RS03 | (-0.8 , 0.34 , 72.47) | 24 | 0.34 | 24 | 14 |
| A211 | Fluidized bed dryer - Heat pump - No | PS12 | HS05 | RS01 | (-0.58 , 0.56 , 71.98) | 23.98 | 0.34 | 23.99 | 15 |
| A189 | Direct rotary dryer - Boiler-mixed typ | PS11 | HS03 | RS03 | (-0.8 , 0.4 , 71.99) | 23.87 | 0.34 | 23.87 | 16 |
| A184 | Direct rotary dryer - Boiler-renewabl | PS11 | HS02 | RS01 | (-0.69 , 0.52 , 71.58) | 23.8 | 0.34 | 23.81 | 17 |
| A079 | Rotary steam tube dryer - Boiler-mix | PS05 | HS03 | RS01 | (-0.6 , 0.61 , 71.22) | 23.74 | 0.34 | 23.75 | 19 |
| A146 | Direct conveyor dryers - Boiler/heate | PS09 | HS01 | RS02 | (-0.65 , 0.49 , 71.19) | 23.68 | 0.34 | 23.68 | 20 |
| A150 | Direct conveyor dryers - Boiler-rene | PS09 | HS02 | RS03 | (-0.66 , 0.46 , 71.03) | 23.61 | 0.34 | 23.61 | 21 |
| A207 | Fluidized bed dryer - Boiler-mixed ty | PS12 | HS03 | RS03 | (-0.8 , 0.37 , 70.64) | 23.4 | 0.34 | 23.4 | 22 |
| A202 | Fluidized bed dryer - Boiler-renewab | PS12 | HS02 | RS01 | (-0.69 , 0.48 , 70.22) | 23.34 | 0.34 | 23.34 | 23 |
| A152 | Direct conveyor dryers - Boiler-mixe | PS09 | HS03 | RS02 | (-0.65 , 0.51 , 69.36) | 23.07 | 0.34 | 23.08 | 24 |
| A181 | Direct rotary dryer - Boiler/heater-no | PS11 | HS01 | RS01 | (-0.69 , 0.45 , 69.08) | 22.95 | 0.34 | 22.95 | 25 |
| A147 | Direct conveyor dryers - Boiler/heate | PS09 | HS01 | RS03 | (-0.66 , 0.39 , 68.52) | 22.75 | 0.34 | 22.75 | 26 |
| A157 | Direct conveyor dryers - Heat pump | PS09 | HS05 | RS01 | (-0.44 , 0.61 , 68.04) | 22.73 | 0.34 | 22.74 | 27 |
| A199 | Fluidized bed dryer - Boiler/heater-n | PS12 | HS01 | RS01 | (-0.69 , 0.41 , 67.72) | 22.48 | 0.34 | 22.48 | 28 |
| A187 | Direct rotary dryer - Boiler-mixed typ | PS11 | HS03 | RS01 | (-0.69 , 0.47 , 67.25) | 22.35 | 0.34 | 22.35 | 29 |
| A153 | Direct conveyor dryers - Boiler-mixe | PS09 | HS03 | RS03 | (-0.66 , 0.42 , 66.7) | 22.15 | 0.34 | 22.15 | 30 |
| A058 | Contact conveyor dryers - Boiler-ren | PS04 | HS02 | RS01 | (-0.42 , 0.54 , 66.22) | 22.11 | 0.34 | 22.11 | 31 |
| A148 | Direct conveyor dryers - Boiler-rene | PS09 | HS02 | RS01 | (-0.55 , 0.53 , 66.28) | 22.09 | 0.34 | 22.09 | 32 |
| A205 | Fluidized bed dryer - Boiler-mixed ty | PS12 | HS03 | RS01 | (-0.69 , 0.44 , 65.89) | 21.88 | 0.34 | 21.88 | 33 |
| A055 | Contact conveyor dryers - Boiler/hea | PS04 | HS01 | RS01 | (-0.43 , 0.47 , 63.72) | 21.25 | 0.34 | 21.26 | 34 |
| A145 | Direct conveyor dryers - Boiler/heate | PS09 | HS01 | RS01 | (-0.55 , 0.47 , 63.78) | 21.23 | 0.34 | 21.24 | 35 |
| A061 | Contact conveyor dryers - Boiler-mix | PS04 | HS03 | RS01 | (-0.43 , 0.5 , 61.89) | 20.65 | 0.34 | 20.66 | 36 |
| A151 | Direct conveyor dryers - Boiler-mixe | PS09 | HS03 | RS01 | (-0.55 , 0.49 , 61.95) | 20.63 | 0.34 | 20.63 | 37 |
| A131 | Direct tunnel dryer - Boiler-renewabl | PS08 | HS02 | RS02 | (-0.6 , 0.45 , 57.46) | 19.11 | 0.34 | 19.11 | 38 |
| A128 | Direct tunnel dryer - Boiler/heater-no | PS08 | HS01 | RS02 | (-0.6 , 0.39 , 54.96) | 18.25 | 0.34 | 18.25 | 39 |
| A132 | Direct tunnel dryer - Boiler-renewabl | PS08 | HS02 | RS03 | (-0.62 , 0.36 , 54.8) | 18.18 | 0.34 | 18.19 | 40 |
| A154 | Direct conveyor dryers - Solar collec | PS09 | HS04 | RS01 | (-0.57 , 0.35 , 54.34) | 18.04 | 0.34 | 18.04 | 41 |
| A134 | Direct tunnel dryer - Boiler-mixed typ | PS08 | HS03 | RS02 | (-0.6 , 0.41 , 53.13) | 17.65 | 0.34 | 17.65 | 42 |
| A129 | Direct tunnel dryer - Boiler/heater-no | PS08 | HS01 | RS03 | (-0.62 , 0.3 , 52.3) | 17.32 | 0.34 | 17.33 | 43 |
| A139 | Direct tunnel dryer - Heat pump - No | PS08 | HS05 | RS01 | (-0.4 , 0.51 , 51.81) | 17.31 | 0.34 | 17.31 | 44 |
| A022 | Contact tunnel dryer - Boiler-renewal | PS02 | HS02 | RS01 | (-0.38 , 0.5 , 50.66) | 16.93 | 0.34 | 16.93 | 45 |
| A135 | Direct tunnel dryer - Boiler-mixed typ | PS08 | HS03 | RS03 | (-0.62 , 0.32 , 50.47) | 16.72 | 0.34 | 16.73 | 46 |
| A130 | Direct tunnel dryer - Boiler-renewabl | PS08 | HS02 | RS01 | (-0.5 , 0.43 , 50.05) | 16.66 | 0.34 | 16.67 | 47 |
| A019 | Contact tunnel dryer - Boiler/heater-r | PS02 | HS01 | RS01 | (-0.38 , 0.43 , 48.16) | 16.07 | 0.34 | 16.07 | 48 |
| A127 | Direct tunnel dryer - Boiler/heater-no | PS08 | HS01 | RS01 | (-0.5 , 0.37 , 47.55) | 15.8 | 0.34 | 15.81 | 49 |
| A025 | Contact tunnel dryer - Boiler-mixed t | PS02 | HS03 | RS01 | (-0.38 , 0.45 , 46.33) | 15.47 | 0.34 | 15.47 | 50 |
| A133 | Direct tunnel dryer - Boiler-mixed typ | PS08 | HS03 | RS01 | (-0.5 , 0.39 , 45.72) | 15.2 | 0.34 | 15.21 | 51 |
| A136 | Direct tunnel dryer - Solar collector - | PS08 | HS04 | RS01 | (-0.52 , 0.25 , 38.12) | 12.61 | 0.34 | 12.62 | 52 |

# Annex 5. Selection of cassava starch dryers

Annex 5-1. Thermodynamic parameters of the drying of cassava starch

| Parameters | Notation | Unit | Value | | |
|---|---|---|---|---|---|
| GENERAL PARAMETERS | | | | | |
| Material and product parameters | | | | | |
| Initial moisture content of feed | wi | kg/kg | (0.32 , 0.33 , 0.34) | | |
| Final moisture content of prod | wo | kg/kg | (0.12 , 0.13 , 0.14) | | |
| Inlet temperature of feed subs | Tmi | oC | (25 , 28 , 30) | | |
| Average specific heat capacit | cpm | kJ/kg.oC | (1.96 , 1.99 , 2.02) | | |
| Specific heat capacity of drie | cpm-o | kJ/kg.oC | (1.69 , 1.73 , 1.77) | | |
| Specific heat, latent heat | | | | | |
| Specific heat capacity of feed | cpm-i | kJ/kg.oC | (2.22 , 2.25 , 2.28) | | |
| Specific heat capacity of dry | Cpa | kJ/kg.oC | (1 , 1 , 1) | | |
| Specific heat capacity of vap | cpv | kJ/kg.oC | (1.86 , 1.87 , 1.88) | | |
| Specific heat of frozen water | cpwf | kJ/kg.oC | (2.1 , 2.1 , 2.1) | | |
| Latent heat of vaporization | ΔHwv | kJ/kg | (2415.9 , 2423.04 , 2431.35) | | |
| | | | | | |
| HOT AIR DRYING | | | GROUP 1 | GROUP 2 | GROUP 3 |
| State 0 Ambient air | | | | | |
| Ambient air temperature | Tamb | oC | (28 , 30 , 32) | (28 , 30 , 32) | (28 , 30 , 32) |
| Relative humidity of ambient a | Yabm | % | (55 , 60 , 65) | (55 , 60 , 65) | (55 , 60 , 65) |
| Ambient air pressure | Pamb | bar | (0.99 , 0.99 , 0.99) | (0.99 , 0.99 , 0.99) | (0.99 , 0.99 , 0.99) |
| Enthalpy of air | ho | J/kg dry air | (60.64 , 70.33 , 81.45) | (60.64 , 70.33 , 81.45) | (60.64 , 70.33 , 81.45) |
| humidity ratio | y0 | g/kg dry air | (0.01 , 0.02 , 0.02) | (0.01 , 0.02 , 0.02) | (0.01 , 0.02 , 0.02) |
| State 1 Inlet drying air (heated air) | | | | | |
| Temperature | T1 | oC | (60 , 70 , 80) | (100 , 110 , 120) | (140 , 150 , 160) |
| Humidity ratio | y1 | g/kg dry air | (0.01 , 0.02 , 0.02) | (0.01 , 0.02 , 0.02) | (0.01 , 0.02 , 0.02) |
| Enthalpy of air | h1 | J/kg dry air | (93.43 , 111.55 , 131.24) | (134.42 , 152.76 , 172.74) | (175.4 , 193.98 , 214.23) |
| Saturation vapour pressure | Ps1 | bar | (0.2 , 0.31 , 0.47) | (1 , 1.41 , 1.96) | (3.59 , 4.74 , 6.17) |
| Relative humidity | Y1 | % | (0.04 , 0.08 , 0.16) | (0.01 , 0.02 , 0.03) | (0 , 0.01 , 0.01) |
| State 2 Outlet drying air (exhaust air) | | | | | |
| Enthalpy of air | h2 | J/kg dry air | (93.43 , 111.55 , 131.24) | (134.42 , 152.76 , 172.74) | (175.4 , 193.98 , 214.23) |
| Dewpoint temperature | Tdp2 | oC | (29 , 32 , 35.5) | (33 , 37 , 45.5) | (39 , 42.5 , 48.5) |
| Temperature | T2 | oC | (39 , 42 , 45.5) | (43 , 47 , 55.5) | (49 , 52.5 , 58.5) |
| Saturation vapour pressure | Ps2 | bar | (0.07 , 0.08 , 0.1) | (0.09 , 0.11 , 0.16) | (0.12 , 0.14 , 0.18) |
| Humidity ratio | y2 | g/kg dry air | (0.02 , 0.03 , 0.03) | (0.04 , 0.04 , 0.05) | (0.05 , 0.06 , 0.06) |
| Relative humidity | Y2 | % | (0.34 , 0.52 , 0.76) | (0.34 , 0.6 , 0.81) | (0.4 , 0.6 , 0.78) |
| | | | | | |
| CONTACT DRYING | | | GROUP 1 | GROUP 2 | GROUP 3 |
| Drying temperature | Td | oC | (40 , 45 , 50) | (40 , 50 , 60) | (60 , 70 , 80) |
| | | | | | |
| HEAT PUMP DRYING | | | | | |
| State 1 | | | | | |
| Temperature | Ta1 | oC | (10 , 12 , 15) | | |
| Relative humidity | Y1 | % | (1 , 1 , 1) | | |
| Saturated vapor pressure | Ps1 | Bar | (0.01 , 0.01 , 0.02) | | |
| Ambient air pressure | B | bar | (0.99 , 0.99 , 0.99) | | |
| Humidity ratio | y1 | kg/kg | (0.01 , 0.01 , 0.01) | | |
| Enthalpy | h1 | kJ/kg | (29.62 , 34.48 , 42.46) | | |
| State 2 | | | | | |
| Temperature | Ta2 | oC | (50 , 55 , 60) | | |
| Relative humidity | y2 | kg/kg | (0.01 , 0.01 , 0.01) | | |
| Enthalpy | h2 | kJ/kg | (70.36 , 78.36 , 88.54) | | |
| State 3 | | | | | |
| Enthalpy | h3 | kJ/kg | (70.36 , 78.36 , 88.54) | | |
| Temperature | Ta3 | oC | (30 , 32 , 35) | | |
| Humidity ratio | y3 | kg/kg | (0.02 , 0.02 , 0.02) | | |
| | | | | | |
| FREEZE DRYING | | | | | |
| Temperature of freeze drying process | | | | | |
| Freezing temperature of water | Twf | oC | (-2 , -1 , 0) | | |
| Freeze drying temperature of | Twfd | oC | (-40 , -30 , -20) | | |
| Specific heat, latent heat | | | | | |
| Latent heat of water freezing | ΔHwf | kJ/kg | (355 , 355 , 355) | | |
| Latent heat of water sublimatio | ΔHws | kJ/kg | (2840 , 2840 , 2840) | | |
| Latent heat of water condensa | ΔHwc | kJ/kg | (2840 , 2840 , 2840) | | |
| Latent heat of water melting | ΔHwm | kJ/kg | (334 , 334 , 334) | | |

# Annex 5-2. Justification of the selected subsystem technologies

| PROCESSING SUBSYSTEM | | SUB-CRITERIA | | | | | | |
|---|---|---|---|---|---|---|---|---|
| ID | Technology | $C_{11}$ | $C_{12}$ | $C_{21}$ | $C_{22}$ | $C_{31}$ | $C_{32}$ | $C_{33}$ |
| PS01 | Contact cabinet dryer | (2465.4 , 2508.67 , 2556.05) | (50 , 65 , 80) | (0.33 , 1 , 3) | (0.2 , 0.33 , 1) | (0.2 , 0.33 , 1) | (0.2 , 0.33 , 1) | (0.2 , 0.33 , 1) |
| PS02 | Contact tunnel dryer | (2465.4 , 2508.67 , 2556.05) | (35 , 47.5 , 60) | (0.33 , 1 , 3) | (0.2 , 0.33 , 1) | (0.2 , 0.33 , 1) | (0.2 , 0.33 , 1) | (0.2 , 0.33 , 1) |
| PS03 | Plate dryer | (2465.4 , 2508.67 , 2556.05) | (50 , 65 , 80) | (0.33 , 1 , 3) | (0.33 , 1 , 3) | (0.33 , 1 , 3) | (0.2 , 0.33 , 1) | (0.2 , 0.33 , 1) |
| PS05 | Rotary steam tube dryer | (2401.7 , 2478.92 , 2560.25) | (75 , 82.5 , 90) | (1 , 3 , 5) | (1 , 3 , 5) | (0.33 , 1 , 3) | (0.33 , 1 , 3) | (1 , 3 , 5) |
| PS07 | Direct cabinet dryer | (1117.08 , 3116.91 , 6849.63) | (50 , 65 , 80) | (0.2 , 0.33 , 1) | (0.2 , 0.33 , 1) | (0.2 , 0.33 , 1) | (0.33 , 1 , 3) | (0.2 , 0.33 , 1) |
| PS08 | Direct tunnel dryer | (1117.08 , 3116.91 , 6849.63) | (35 , 37.5 , 40) | (0.2 , 0.33 , 1) | (0.2 , 0.33 , 1) | (0.2 , 0.33 , 1) | (0.33 , 1 , 3) | (0.33 , 1 , 3) |
| PS11 | Direct rotary dryer | (1603.23 , 3178.27 , 5423.7) | (40 , 55 , 70) | (0.33 , 1 , 3) | (1 , 3 , 5) | (0.33 , 1 , 3) | (1 , 3 , 5) | (3 , 5 , 5) |
| PS12 | Fluidized bed dryer | (1603.23 , 3178.27 , 5423.7) | (40 , 60 , 80) | (0.33 , 1 , 3) | (1 , 3 , 5) | (0.33 , 1 , 3) | (1 , 3 , 5) | (0.33 , 1 , 3) |
| PS15 | Pneumatic flash dryer | (1951.32 , 3093.14 , 4331.68) | (50 , 62.5 , 75) | (0.33 , 1 , 3) | (0.33 , 1 , 3) | (1 , 3 , 5) | (1 , 3 , 5) | (0.33 , 1 , 3) |
| PS16 | Freeze dryer | (2794.56 , 4784.11 , 7391.77) | (10 , 15 , 20) | (3 , 5 , 5) | (3 , 5 , 5) | (3 , 5 , 5) | (0.2 , 0.2 , 0.33) | (0.2 , 0.33 , 1) |

| HEATING SUBSYSTEM | | SUB-CRITERIA | | | | | | |
|---|---|---|---|---|---|---|---|---|
| ID | Technology | $C_{12}$ | $C_{14}$ | $C_{21}$ | $C_{22}$ | $C_{31}$ | $C_{32}$ | $C_{33}$ |
| HS01 | Boiler/heater-non renewable en | (70 , 77.5 , 85) | (0 , 0 , 0) | (0.33 , 1 , 3) | (0.33 , 1 , 3) | (0.33 , 1 , 3) | (0.33 , 1 , 3) | (0.33 , 1 , 3) |
| HS02 | Boiler-renewable energy | (70 , 72.5 , 75) | (100 , 100 , 100) | (0.33 , 1 , 3) | (0.33 , 1 , 3) | (0.33 , 1 , 3) | (0.33 , 1 , 3) | (0.33 , 1 , 3) |
| HS03 | Boiler-mixed type | (70 , 75 , 80) | (30 , 50 , 70) | (0.33 , 1 , 3) | (0.33 , 1 , 3) | (0.33 , 1 , 3) | (0.33 , 1 , 3) | (0.2 , 0.33 , 1) |
| HS04 | Solar collector | (40 , 50 , 60) | (100 , 100 , 100) | (1 , 3 , 5) | (1 , 3 , 5) | (0.2 , 0.33 , 1) | (0.2 , 0.33 , 1) | (0.2 , 0.33 , 1) |
| HS05 | Heat pump | (90 , 95 , 100) | (0 , 0 , 0) | (0.2 , 0.33 , 1) | (0.2 , 0.33 , 1) | (1 , 3 , 5) | (0.2 , 0.33 , 1) | (0.2 , 0.33 , 1) |
| HS06 | Refrigeration plant | (10 , 15 , 20) | (0 , 0 , 0) | (3 , 5 , 5) | (3 , 5 , 5) | (3 , 5 , 5) | (0.2 , 0.2 , 0.33) | (0.2 , 0.33 , 1) |

| HEAT RECOVERY SUBSYSTEM | | SUB-CRITERIA | | | | | |
|---|---|---|---|---|---|---|---|
| ID | Technology | $C_{13}$ | $C_{21}$ | $C_{22}$ | $C_{31}$ | $C_{32}$ | $C_{33}$ |
| RS01 | No heat recovery | (0 , 0 , 0) | (0.2 , 0.2 , 0.33) | (0.2 , 0.2 , 0.33) | (1 , 3 , 5) | (0.2 , 0.33 , 1) | (1 , 3 , 5) |
| RS02 | Exhaust air recirculation | (15 , 32.5 , 50) | (0.2 , 0.33 , 1) | (0.33 , 1 , 3) | (0.2 , 0.33 , 1) | (1 , 3 , 5) | (0.33 , 1 , 3) |
| RS03 | Exhaust air heat exchanger | (10 , 20 , 30) | (1 , 3 , 5) | (1 , 3 , 5) | (1 , 3 , 5) | (0.2 , 0.33 , 1) | (0.2 , 0.33 , 1) |

## Annex 5-3. Normalization data - aggregated normalization method

| PROCESSING SUBSYSTEM | | SUB-CRITERIA | | | | | | |
|---|---|---|---|---|---|---|---|---|
| ID | Technology | $C_{11}$ | $C_{12}$ | $C_{21}$ | $C_{22}$ | $C_{31}$ | $C_{32}$ | $C_{33}$ |
| PS01 | Contact cabinet dryer | (-4.26 , -0.55 , -0.1) | (0.3 , 2.34 , 12.26) | (-5.28 , -0.5 , -0.06) | (-2.61 , -0.24 , -0.05) | (0.03 , 0.45 , 8.87) | (-5.15 , -0.15 , -0.02) | (0.02 , 0.16 , 4.12) |
| PS02 | Contact tunnel dryer | (-4.26 , -0.55 , -0.1) | (0.21 , 1.71 , 9.2) | (-5.28 , -0.5 , -0.06) | (-2.61 , -0.24 , -0.05) | (0.03 , 0.45 , 8.87) | (-5.15 , -0.15 , -0.02) | (0.02 , 0.16 , 4.12) |
| PS03 | Plate dryer | (-4.26 , -0.55 , -0.1) | (0.3 , 2.34 , 12.26) | (-5.28 , -0.5 , -0.06) | (-7.84 , -0.73 , -0.08) | (0.05 , 1.35 , 26.61) | (-5.15 , -0.15 , -0.02) | (0.02 , 0.16 , 4.12) |
| PS05 | Rotary steam tube dryer | (-4.27 , -0.54 , -0.1) | (0.44 , 2.97 , 13.79) | (-8.8 , -1.5 , -0.19) | (-13.07 , -2.19 , -0.24) | (0.05 , 1.35 , 26.61) | (-15.45 , -0.45 , -0.03) | (0.09 , 1.42 , 20.6) |
| PS07 | Direct cabinet dryer | (-11.42 , -0.68 , -0.04) | (0.3 , 2.34 , 12.26) | (-1.76 , -0.17 , -0.04) | (-2.61 , -0.24 , -0.05) | (0.03 , 0.45 , 8.87) | (-15.45 , -0.45 , -0.03) | (0.02 , 0.16 , 4.12) |
| PS08 | Direct tunnel dryer | (-11.42 , -0.68 , -0.04) | (0.21 , 1.35 , 6.13) | (-1.76 , -0.17 , -0.04) | (-2.61 , -0.24 , -0.05) | (0.03 , 0.45 , 8.87) | (-15.45 , -0.45 , -0.03) | (0.03 , 0.47 , 12.36) |
| PS11 | Direct rotary dryer | (-9.05 , -0.7 , -0.06) | (0.24 , 1.98 , 10.73) | (-5.28 , -0.5 , -0.06) | (-13.07 , -2.19 , -0.24) | (0.05 , 1.35 , 26.61) | (-25.76 , -1.36 , -0.08) | (0.27 , 2.37 , 20.6) |
| PS12 | Fluidized bed dryer | (-9.05 , -0.7 , -0.06) | (0.24 , 2.16 , 12.26) | (-5.28 , -0.5 , -0.06) | (-13.07 , -2.19 , -0.24) | (0.05 , 1.35 , 26.61) | (-25.76 , -1.36 , -0.08) | (0.03 , 0.47 , 12.36) |
| PS15 | Pneumatic flash dryer | (-7.23 , -0.68 , -0.08) | (0.3 , 2.25 , 11.49) | (-5.28 , -0.5 , -0.06) | (-7.84 , -0.73 , -0.08) | (0.16 , 4.05 , 44.34) | (-25.76 , -1.36 , -0.08) | (0.03 , 0.47 , 12.36) |
| PS16 | Freeze dryer | (-12.33 , -1.05 , -0.11) | (0.06 , 0.54 , 3.07) | (-8.8 , -2.5 , -0.57) | (-13.07 , -3.66 , -0.73) | (0.49 , 6.75 , 44.34) | (-1.72 , -0.09 , -0.02) | (0.02 , 0.16 , 4.12) |
| **HEATING SUBSYSTEM** | | **SUB-CRITERIA** | | | | | | |
| ID | Technology | $C_{12}$ | $C_{14}$ | $C_{21}$ | $C_{22}$ | $C_{31}$ | $C_{32}$ | $C_{33}$ |
| HS01 | Boiler/heater-non renewable en | (0.4 , 2.42 , 9.71) | (0 , 0 , 0) | (-3.9 , -0.39 , -0.06) | (-6.76 , -0.67 , -0.07) | (0.04 , 0.95 , 18.83) | (-27.82 , -0.93 , -0.04) | (0.04 , 1.08 , 30.34) |
| HS02 | Boiler-renewable energy | (0.4 , 2.26 , 8.57) | (0.41 , 1.6 , 8.7) | (-3.9 , -0.39 , -0.06) | (-6.76 , -0.67 , -0.07) | (0.04 , 0.95 , 18.83) | (-27.82 , -0.93 , -0.04) | (0.04 , 1.08 , 30.34) |
| HS03 | Boiler-mixed type | (0.4 , 2.34 , 9.14) | (0.12 , 0.8 , 6.09) | (-3.9 , -0.39 , -0.06) | (-6.76 , -0.67 , -0.07) | (0.04 , 0.95 , 18.83) | (-27.82 , -0.93 , -0.04) | (0.03 , 0.36 , 10.11) |
| HS04 | Solar collector | (0.23 , 1.56 , 6.86) | (0.41 , 1.6 , 8.7) | (-6.5 , -1.16 , -0.17) | (-11.26 , -2.01 , -0.22) | (0.03 , 0.32 , 6.28) | (-9.27 , -0.31 , -0.02) | (0.03 , 0.36 , 10.11) |
| HS05 | Heat pump | (0.51 , 2.96 , 11.43) | (0 , 0 , 0) | (-1.3 , -0.13 , -0.03) | (-2.25 , -0.22 , -0.04) | (0.13 , 2.86 , 31.38) | (-9.27 , -0.31 , -0.02) | (0.03 , 0.36 , 10.11) |
| HS06 | Refrigeration plant | (0.06 , 0.47 , 2.29) | (0 , 0 , 0) | (-6.5 , -1.94 , -0.51) | (-11.26 , -3.36 , -0.66) | (0.39 , 4.76 , 31.38) | (-3.09 , -0.19 , -0.02) | (0.03 , 0.36 , 10.11) |
| **HEAT RECOVERY SUBSYSTEM** | | **SUB-CRITERIA** | | | | | | |
| ID | Technology | $C_{13}$ | $C_{21}$ | $C_{22}$ | $C_{31}$ | $C_{32}$ | $C_{33}$ | |
| RS01 | No heat recovery | (0 , 0 , 0) | (-0.81 , -0.12 , -0.05) | (-1.27 , -0.18 , -0.05) | (0.12 , 2.56 , 37.09) | (-5.3 , -0.16 , -0.02) | (0.07 , 1.25 , 24.19) | |
| RS02 | Exhaust air recirculation | (0.11 , 1.24 , 20) | (-2.42 , -0.21 , -0.05) | (-11.46 , -0.91 , -0.09) | (0.02 , 0.28 , 7.42) | (-26.49 , -1.47 , -0.09) | (0.02 , 0.42 , 14.51) | |
| RS03 | Exhaust air heat exchanger | (0.07 , 0.76 , 12) | (-12.08 , -1.86 , -0.27) | (-19.1 , -2.72 , -0.26) | (0.12 , 2.56 , 37.09) | (-5.3 , -0.16 , -0.02) | (0.01 , 0.14 , 4.84) | |

## Annex 5-4. Aggregate the ratings of technology alternatives along the hierarchy - application for the selection of new facilities

| PROCESSING SUBSYSTEM | | CRITERIA | | | OBJECTIVE |
|---|---|---|---|---|---|
| ID | Technology | $C_1$ | $C_2$ | $C_3$ | O |
| PS01 | Contact cabinet dryer | (-1.98 , 0.9 , 6.08) | (-3.95 , -0.37 , -0.06) | (-1.7 , 0.15 , 4.32) | (-0.7 , 0.49 , 14.54) |
| PS02 | Contact tunnel dryer | (-2.03 , 0.58 , 4.55) | (-3.95 , -0.37 , -0.06) | (-1.7 , 0.15 , 4.32) | (-0.7 , 0.3 , 11.76) |
| PS03 | Plate dryer | (-1.98 , 0.9 , 6.08) | (-6.56 , -0.62 , -0.07) | (-1.69 , 0.45 , 10.24) | (-0.89 , 0.51 , 19.4) |
| PS05 | Rotary steam tube dryer | (-1.91 , 1.22 , 6.85) | (-10.94 , -1.85 , -0.22) | (-5.1 , 0.77 , 15.73) | (-1.44 , 0.51 , 25.2) |
| PS07 | Direct cabinet dryer | (-5.56 , 0.83 , 6.11) | (-2.19 , -0.21 , -0.04) | (-5.13 , 0.05 , 4.32) | (-1.33 , 0.47 , 14.6) |
| PS08 | Direct tunnel dryer | (-5.61 , 0.33 , 3.04) | (-2.19 , -0.21 , -0.04) | (-5.13 , 0.16 , 7.07) | (-1.34 , 0.19 , 11.31) |
| PS11 | Direct rotary dryer | (-4.4 , 0.64 , 5.33) | (-9.18 , -1.35 , -0.15) | (-8.48 , 0.78 , 15.71) | (-1.92 , 0.27 , 22.49) |
| PS12 | Fluidized bed dryer | (-4.4 , 0.73 , 6.1) | (-9.18 , -1.35 , -0.15) | (-8.56 , 0.15 , 12.96) | (-1.92 , 0.2 , 21.61) |
| PS15 | Pneumatic flash dryer | (-3.46 , 0.79 , 5.71) | (-6.56 , -0.62 , -0.07) | (-8.52 , 1.05 , 18.88) | (-1.6 , 0.56 , 25.85) |
| PS16 | Freeze dryer | (-6.13 , -0.25 , 1.48) | (-10.94 , -3.08 , -0.65) | (-0.4 , 2.27 , 16.15) | (-1.7 , -0.31 , 15.45) |
| **HEATING SUBSYSTEM** | | **CRITERIA** | | | **OBJECTIVE** |
| ID | Technology | $C_1$ | $C_2$ | $C_3$ | O |
| HS01 | Boiler/heater-non renewable energy | (0.2 , 1.21 , 4.86) | (-5.33 , -0.53 , -0.06) | (-9.24 , 0.37 , 16.38) | (-1.04 , 0.69 , 22.25) |
| HS02 | Boiler-renewable energy | (0.41 , 1.93 , 8.63) | (-5.33 , -0.53 , -0.06) | (-9.24 , 0.37 , 16.38) | (-1.01 , 1.13 , 29.1) |
| HS03 | Boiler-mixed type | (0.26 , 1.57 , 7.61) | (-5.33 , -0.53 , -0.06) | (-9.25 , 0.13 , 9.64) | (-1.03 , 0.86 , 21.69) |
| HS04 | Solar collector | (0.32 , 1.58 , 7.78) | (-8.88 , -1.59 , -0.19) | (-3.07 , 0.12 , 5.46) | (-0.83 , 0.65 , 18.44) |
| HS05 | Heat pump | (0.26 , 1.48 , 5.71) | (-1.78 , -0.18 , -0.04) | (-3.04 , 0.97 , 13.82) | (-0.31 , 1.05 , 21.72) |
| HS06 | Refrigeration plant | (0.03 , 0.23 , 1.14) | (-8.88 , -2.65 , -0.58) | (-0.89 , 1.65 , 13.82) | (-0.71 , -0.06 , 12.98) |
| **HEAT RECOVERY SUBSYSTEM** | | **CRITERIA** | | | **OBJECTIVE** |
| ID | Technology | $C_1$ | $C_2$ | $C_3$ | O |
| RS01 | No heat recovery | (0 , 0 , 0) | (-1.04 , -0.15 , -0.05) | (-1.7 , 1.21 , 20.42) | (-0.2 , 0.21 , 16.78) |
| RS02 | Exhaust air recirculation | (0.11 , 1.24 , 20) | (-6.94 , -0.56 , -0.07) | (-8.81 , -0.26 , 7.28) | (-1.14 , 0.58 , 42.2) |
| RS03 | Exhaust air heat exchanger | (0.07 , 0.76 , 12) | (-15.59 , -2.29 , -0.27) | (-1.72 , 0.84 , 13.97) | (-1.25 , 0.17 , 33.05) |

## Annex 5-5. Defuzzification - application for the selection of new facilities

| PROCESSING SUBSYSTEM | | FUZZY RATING | DEFFUZIFICATION | | | RANKING |
|---|---|---|---|---|---|---|
| ID | Technology | $r_{PS}$ | $x_{PS}$ | $y_{PS}$ | $R_{PS}$ | |
| PS15 | Pneumatic flash dryer | (-1.6 , 0.56 , 25.85) | 8.27 | 0.348 | 8.278 | 1 |
| PS05 | Rotary steam tube dryer | (-1.44 , 0.51 , 25.2) | 8.091 | 0.347 | 8.098 | 2 |
| PS11 | Direct rotary dryer | (-1.92 , 0.27 , 22.49) | 6.948 | 0.342 | 6.957 | 3 |
| PS12 | Fluidized bed dryer | (-1.92 , 0.2 , 21.61) | 6.63 | 0.34 | 6.639 | 4 |
| PS03 | Plate dryer | (-0.89 , 0.51 , 19.4) | 6.341 | 0.351 | 6.351 | 5 |
| PS01 | Contact cabinet dryer | (-0.7 , 0.49 , 14.54) | 4.781 | 0.356 | 4.794 | 6 |
| PS07 | Direct cabinet dryer | (-1.33 , 0.47 , 14.6) | 4.579 | 0.355 | 4.593 | 7 |
| PS16 | Freeze dryer | (-1.7 , -0.31 , 15.45) | 4.478 | 0.317 | 4.49 | 8 |
| PS02 | Contact tunnel dryer | (-0.7 , 0.3 , 11.76) | 3.789 | 0.351 | 3.805 | 9 |
| PS08 | Direct tunnel dryer | (-1.34 , 0.19 , 11.31) | 3.387 | 0.346 | 3.405 | 10 |
| **HEATING SUBSYSTEM** | | **FUZZY RATING** | **DEFFUZIFICATION** | | | **RANKING** |
| ID | Technology | $r_{HS}$ | $x_{HS}$ | $y_{HS}$ | $R_{HS}$ | |
| HS02 | Boiler-renewable energy | (-1.01 , 1.13 , 29.1) | 9.74 | 0.358 | 9.746 | 1 |
| HS05 | Heat pump | (-0.31 , 1.05 , 21.72) | 7.485 | 0.363 | 7.494 | 2 |
| HS01 | Boiler/heater-non renewable ener | (-1.04 , 0.69 , 22.25) | 7.303 | 0.354 | 7.312 | 3 |
| HS03 | Boiler-mixed type | (-1.03 , 0.86 , 21.69) | 7.176 | 0.359 | 7.185 | 4 |
| HS04 | Solar collector | (-0.83 , 0.65 , 18.44) | 6.088 | 0.356 | 6.098 | 5 |
| HS06 | Refrigeration plant | (-0.71 , -0.06 , 12.98) | 4.072 | 0.33 | 4.085 | 6 |
| **HEAT RECOVERY SUBSYSTEM** | | **FUZZY RATING** | **DEFFUZIFICATION** | | | **RANKING** |
| ID | Technology | $r_{RS}$ | $x_{RS}$ | $y_{RS}$ | $R_{RS}$ | |
| RS02 | Exhaust air recirculation | (-1.14 , 0.58 , 42.2) | 13.883 | 0.342 | 13.887 | 1 |
| RS03 | Exhaust air heat exchanger | (-1.25 , 0.17 , 33.05) | 10.655 | 0.337 | 10.661 | 2 |
| RS01 | No heat recovery | (-0.2 , 0.21 , 16.78) | 5.599 | 0.342 | 5.609 | 3 |

Annex 5-6. Normalization data - base-cased normalization method

| PROCESSING SUBSYSTEM | | SUB-CRITERIA | | | | | | |
|---|---|---|---|---|---|---|---|---|
| ID | Technology | $C_{11}$ | $C_{12}$ | $C_{21}$ | $C_{22}$ | $C_{31}$ | $C_{32}$ | $C_{33}$ |
| PSbc | Pneumatic flash dryer | (-13.74 , -1.5 , -0.26) | (0.14 , 1.13 , 5.65) | (-7.32 , -0.6 , -0.06) | (-11.74 , -0.96 , -0.08) | (0.12 , 2.7 , 34.73) | (-18.54 , -0.52 , -0.03) | (0.03 , 0.53 , 16.59) |
| PS01 | Contact cabinet dryer | (-1.62 , -0.24 , -0.05) | (0.55 , 4.13 , 22.83) | (-7.32 , -0.6 , -0.06) | (-3.91 , -0.32 , -0.05) | (0.02 , 0.3 , 6.95) | (-6.18 , -0.17 , -0.02) | (0.02 , 0.18 , 5.53) |
| PS02 | Contact tunnel dryer | (-1.62 , -0.24 , -0.05) | (0.38 , 3.02 , 17.12) | (-7.32 , -0.6 , -0.06) | (-3.91 , -0.32 , -0.05) | (0.02 , 0.3 , 6.95) | (-6.18 , -0.17 , -0.02) | (0.02 , 0.18 , 5.53) |
| PS03 | Plate dryer | (-1.62 , -0.24 , -0.05) | (0.55 , 4.13 , 22.83) | (-7.32 , -0.6 , -0.06) | (-11.74 , -0.96 , -0.08) | (0.04 , 0.9 , 20.84) | (-6.18 , -0.17 , -0.02) | (0.02 , 0.18 , 5.53) |
| PS05 | Rotary steam tube dryer | (-1.62 , -0.24 , -0.04) | (0.82 , 5.25 , 25.68) | (-12.2 , -1.81 , -0.19) | (-19.56 , -2.89 , -0.24) | (0.04 , 0.9 , 20.84) | (-18.54 , -0.52 , -0.03) | (0.08 , 1.6 , 27.64) |
| PS07 | Direct cabinet dryer | (-4.34 , -0.3 , -0.02) | (0.55 , 4.13 , 22.83) | (-2.44 , -0.2 , -0.04) | (-3.91 , -0.32 , -0.05) | (0.02 , 0.3 , 6.95) | (-18.54 , -0.52 , -0.03) | (0.02 , 0.18 , 5.53) |
| PS08 | Direct tunnel dryer | (-4.34 , -0.3 , -0.02) | (0.38 , 2.39 , 11.41) | (-2.44 , -0.2 , -0.04) | (-3.91 , -0.32 , -0.05) | (0.02 , 0.3 , 6.95) | (-18.54 , -0.52 , -0.03) | (0.03 , 0.53 , 16.59) |
| PS11 | Direct rotary dryer | (-3.44 , -0.31 , -0.03) | (0.44 , 3.5 , 19.97) | (-7.32 , -0.6 , -0.06) | (-19.56 , -2.89 , -0.24) | (0.04 , 0.9 , 20.84) | (-30.91 , -1.57 , -0.08) | (0.24 , 2.67 , 27.64) |
| PS12 | Fluidized bed dryer | (-3.44 , -0.31 , -0.03) | (0.44 , 3.82 , 22.83) | (-7.32 , -0.6 , -0.06) | (-19.56 , -2.89 , -0.24) | (0.04 , 0.9 , 20.84) | (-30.91 , -1.57 , -0.08) | (0.03 , 0.53 , 16.59) |
| PS15 | Pneumatic flash dryer | (-2.75 , -0.3 , -0.04) | (0.55 , 3.98 , 21.4) | (-7.32 , -0.6 , -0.06) | (-11.74 , -0.96 , -0.08) | (0.12 , 2.7 , 34.73) | (-30.91 , -1.57 , -0.08) | (0.03 , 0.53 , 16.59) |
| PS16 | Freeze dryer | (-4.68 , -0.47 , -0.05) | (0.11 , 0.95 , 5.71) | (-12.2 , -3.02 , -0.57) | (-19.56 , -4.82 , -0.73) | (0.36 , 4.5 , 34.73) | (-2.06 , -0.1 , -0.02) | (0.02 , 0.18 , 5.53) |
| HEATING SUBSYSTEM | | SUB-CRITERIA | | | | | | |
| ID | Technology | $C_{12}$ | $C_{14}$ | $C_{21}$ | $C_{22}$ | $C_{31}$ | $C_{32}$ | $C_{33}$ |
| HSbc | Boiler-renewable energy | (0.23 , 2.12 , 12.67) | (0.28 , 1.03 , 5.38) | (-6.29 , -0.53 , -0.06) | (-10.9 , -0.92 , -0.08) | (0.05 , 1.31 , 30.36) | (-24.88 , -0.75 , -0.03) | (0.03 , 0.8 , 25.99) |
| HS01 | Boiler/heater-non renewable en | (0.33 , 2.28 , 10.77) | (0 , 0 , 0) | (-6.29 , -0.53 , -0.06) | (-10.9 , -0.92 , -0.08) | (0.05 , 1.31 , 30.36) | (-24.88 , -0.75 , -0.03) | (0.03 , 0.8 , 25.99) |
| HS02 | Boiler-renewable energy | (0.33 , 2.13 , 9.51) | (0.28 , 1.03 , 5.38) | (-6.29 , -0.53 , -0.06) | (-10.9 , -0.92 , -0.08) | (0.05 , 1.31 , 30.36) | (-24.88 , -0.75 , -0.03) | (0.03 , 0.8 , 25.99) |
| HS03 | Boiler-mixed type | (0.33 , 2.21 , 10.14) | (0.08 , 0.52 , 3.77) | (-6.29 , -0.53 , -0.06) | (-10.9 , -0.92 , -0.08) | (0.05 , 1.31 , 30.36) | (-24.88 , -0.75 , -0.03) | (0.02 , 0.27 , 8.66) |
| HS04 | Solar collector | (0.19 , 1.47 , 7.6) | (0.28 , 1.03 , 5.38) | (-10.48 , -1.6 , -0.18) | (-18.16 , -2.77 , -0.23) | (0.03 , 0.44 , 10.12) | (-8.29 , -0.25 , -0.02) | (0.02 , 0.27 , 8.66) |
| HS05 | Heat pump | (0.43 , 2.79 , 12.67) | (0 , 0 , 0) | (-2.1 , -0.18 , -0.04) | (-3.63 , -0.31 , -0.05) | (0.14 , 3.93 , 50.6) | (-8.29 , -0.25 , -0.02) | (0.02 , 0.27 , 8.66) |
| HS06 | Refrigeration plant | (0.05 , 0.44 , 2.53) | (0 , 0 , 0) | (-10.48 , -2.66 , -0.54) | (-18.16 , -4.61 , -0.69) | (0.41 , 6.55 , 50.6) | (-2.76 , -0.15 , -0.02) | (0.02 , 0.27 , 8.66) |
| HEAT RECOVERY SUBSYSTEM | | SUB-CRITERIA | | | | | | |
| ID | Technology | $C_{13}$ | $C_{21}$ | $C_{22}$ | $C_{31}$ | $C_{32}$ | $C_{33}$ | |
| RSbc | No heat recovery | (0 , 0 , 0) | (-1.23 , -0.3 , -0.14) | (-2.04 , -0.48 , -0.15) | (0.1 , 2.15 , 31.76) | (-8.09 , -0.31 , -0.03) | (0.06 , 0.86 , 17.29) | |
| RS01 | No heat recovery | (0 , 0 , 0) | (-1.23 , -0.3 , -0.14) | (-2.04 , -0.48 , -0.15) | (0.1 , 2.15 , 31.76) | (-8.09 , -0.31 , -0.03) | (0.06 , 0.86 , 17.29) | |
| RS02 | Exhaust air recirculation | (0.11 , 1.24 , 20) | (-3.69 , -0.5 , -0.14) | (-18.32 , -2.4 , -0.25) | (0.02 , 0.24 , 6.35) | (-40.47 , -2.82 , -0.14) | (0.02 , 0.29 , 10.38) | |
| RS03 | Exhaust air heat exchanger | (0.07 , 0.76 , 12) | (-18.45 , -4.52 , -0.68) | (-30.53 , -7.19 , -0.76) | (0.1 , 2.15 , 31.76) | (-8.09 , -0.31 , -0.03) | (0.01 , 0.1 , 3.46) | |

Annex 5-7. Aggregate the ratings of technology alternatives along the hierarchy with reference to the base-case alternative

| PROCESSING SUBSYSTEM | | CRITERIA | | | OBJECTIVE |
|---|---|---|---|---|---|
| ID | Technology | $C_1$ | $C_2$ | $C_3$ | O |
| PSbc | Pneumatic flash dryer | (-6.8 , -0.18 , 2.7) | (-9.53 , -0.78 , -0.07) | (-6.13 , 0.9 , 17.1) | (-2.12 , -0.08 , 18.92) |
| PS01 | Contact cabinet dryer | (-0.54 , 1.94 , 11.39) | (-5.62 , -0.46 , -0.06) | (-2.05 , 0.1 , 4.15) | (-0.64 , 1.09 , 24.03) |
| PS02 | Contact tunnel dryer | (-0.62 , 1.39 , 8.54) | (-5.62 , -0.46 , -0.06) | (-2.05 , 0.1 , 4.15) | (-0.65 , 0.76 , 18.86) |
| PS03 | Plate dryer | (-0.54 , 1.94 , 11.39) | (-9.53 , -0.78 , -0.07) | (-2.04 , 0.3 , 8.78) | (-0.92 , 1.07 , 27.83) |
| PS05 | Rotary steam tube dryer | (-0.4 , 2.5 , 12.82) | (-15.88 , -2.35 , -0.22) | (-6.14 , 0.66 , 16.15) | (-1.67 , 1.16 , 36.37) |
| PS07 | Direct cabinet dryer | (-1.9 , 1.92 , 11.4) | (-3.18 , -0.26 , -0.04) | (-6.17 , -0.01 , 4.15) | (-0.95 , 1.09 , 24.06) |
| PS08 | Direct tunnel dryer | (-1.98 , 1.04 , 5.7) | (-3.18 , -0.26 , -0.04) | (-6.16 , 0.1 , 7.84) | (-0.96 , 0.59 , 16.75) |
| PS11 | Direct rotary dryer | (-1.5 , 1.59 , 9.97) | (-13.44 , -1.75 , -0.15) | (-10.21 , 0.67 , 16.13) | (-1.94 , 0.74 , 31.25) |
| PS12 | Fluidized bed dryer | (-1.5 , 1.75 , 11.4) | (-13.44 , -1.75 , -0.15) | (-10.28 , -0.04 , 12.45) | (-1.95 , 0.69 , 30.8) |
| PS15 | Pneumatic flash dryer | (-1.1 , 1.84 , 10.68) | (-9.53 , -0.78 , -0.07) | (-10.25 , 0.56 , 17.08) | (-1.6 , 1.06 , 33.39) |
| PS16 | Freeze dryer | (-2.29 , 0.24 , 2.83) | (-15.88 , -3.92 , -0.65) | (-0.56 , 1.52 , 13.41) | (-1.53 , -0.33 , 15.65) |
| HEATING SUBSYSTEM | | CRITERIA | | | OBJECTIVE |
| ID | Technology | $C_1$ | $C_2$ | $C_3$ | O |
| HSbc | Boiler-renewable energy | (0.25 , 1.58 , 9.03) | (-8.59 , -0.73 , -0.07) | (-8.27 , 0.46 , 18.77) | (-1.19 , 0.89 , 31.79) |
| HS01 | Boiler/heater-non renewable energy | (0.17 , 1.14 , 5.39) | (-8.59 , -0.73 , -0.07) | (-8.27 , 0.46 , 18.77) | (-1.21 , 0.63 , 25.18) |
| HS02 | Boiler-renewable energy | (0.31 , 1.58 , 7.44) | (-8.59 , -0.73 , -0.07) | (-8.27 , 0.46 , 18.77) | (-1.19 , 0.9 , 28.91) |
| HS03 | Boiler-mixed type | (0.21 , 1.36 , 6.95) | (-8.59 , -0.73 , -0.07) | (-8.27 , 0.28 , 13) | (-1.2 , 0.73 , 23.26) |
| HS04 | Solar collector | (0.23 , 1.25 , 6.49) | (-14.32 , -2.18 , -0.21) | (-2.75 , 0.15 , 6.25) | (-1.21 , 0.34 , 16.76) |
| HS05 | Heat pump | (0.22 , 1.4 , 6.34) | (-2.86 , -0.24 , -0.04) | (-2.71 , 1.32 , 19.75) | (-0.38 , 1.05 , 27.73) |
| HS06 | Refrigeration plant | (0.02 , 0.22 , 1.27) | (-14.32 , -3.64 , -0.62) | (-0.78 , 2.22 , 19.75) | (-1.1 , -0.15 , 18.07) |
| HEAT RECOVERY SUBSYSTEM | | CRITERIA | | | OBJECTIVE |
| ID | Technology | $C_1$ | $C_2$ | $C_3$ | O |
| RSbc | No heat recovery | (0 , 0 , 0) | (-1.63 , -0.39 , -0.14) | (-2.65 , 0.9 , 16.34) | (-0.31 , 0.1 , 13.35) |
| HS01 | Boiler/heater-non renewable energy | (0 , 0 , 0) | (-1.63 , -0.39 , -0.14) | (-2.65 , 0.9 , 16.34) | (-0.31 , 0.1 , 13.35) |
| RS02 | Exhaust air recirculation | (0.11 , 1.24 , 20) | (-11 , -1.45 , -0.19) | (-13.48 , -0.76 , 5.53) | (-1.77 , 0.3 , 40.66) |
| RS03 | Exhaust air heat exchanger | (0.07 , 0.76 , 12) | (-24.49 , -5.86 , -0.72) | (-2.66 , 0.64 , 11.73) | (-1.97 , -0.59 , 30.83) |

Annex 5-8. Defuzzification - application for changing of the used technology

| PROCESSING SUBSYSTEM | | FUZZY RATING | DEFFUZIFICATION | | | RANKING |
|---|---|---|---|---|---|---|
| ID | Technology | $r_{PS}$ | $x_{PS}$ | $y_{PS}$ | $R_{PS}$ | |
| PSbc | Pneumatic flash dryer | (-2.12 , -0.08 , 18.92) | 5.575 | 0.33 | 5.584 | 9 |
| PS05 | Rotary steam tube dryer | (-1.67 , 1.16 , 36.37) | 11.957 | 0.354 | 11.963 | 1 |
| PS15 | Pneumatic flash dryer | (-1.6 , 1.06 , 33.39) | 10.947 | 0.354 | 10.952 | 2 |
| PS11 | Direct rotary dryer | (-1.94 , 0.74 , 31.25) | 10.017 | 0.349 | 10.023 | 3 |
| PS12 | Fluidized bed dryer | (-1.95 , 0.69 , 30.8) | 9.85 | 0.349 | 9.856 | 4 |
| PS03 | Plate dryer | (-0.92 , 1.07 , 27.83) | 9.327 | 0.358 | 9.334 | 5 |
| PS01 | Contact cabinet dryer | (-0.64 , 1.09 , 24.03) | 8.163 | 0.362 | 8.171 | 6 |
| PS07 | Direct cabinet dryer | (-0.95 , 1.09 , 24.06) | 8.067 | 0.362 | 8.075 | 7 |
| PS02 | Contact tunnel dryer | (-0.65 , 0.76 , 18.86) | 6.323 | 0.359 | 6.333 | 8 |
| PS08 | Direct tunnel dryer | (-0.96 , 0.59 , 16.75) | 5.46 | 0.357 | 5.471 | 9 |
| PS16 | Freeze dryer | (-1.53 , -0.33 , 15.65) | 4.596 | 0.317 | 4.606 | 10 |
| HEATING SUBSYSTEM | | FUZZY RATING | DEFFUZIFICATION | | | RANKING |
| ID | Technology | $r_{HS}$ | $x_{HS}$ | $y_{HS}$ | $R_{HS}$ | |
| HSbc | Boiler-renewable energy | (-1.19 , 0.89 , 31.79) | 10.494 | 0.352 | 10.5 | 1 |
| HS02 | Boiler-renewable energy | (-1.19 , 0.9 , 28.91) | 9.54 | 0.354 | 9.547 | 1 |
| HS05 | Heat pump | (-0.38 , 1.05 , 27.73) | 9.47 | 0.357 | 9.476 | 2 |
| HS01 | Boiler/heater-non renewable ener | (-1.21 , 0.63 , 25.18) | 8.201 | 0.35 | 8.209 | 3 |
| HS03 | Boiler-mixed type | (-1.2 , 0.73 , 23.26) | 7.596 | 0.354 | 7.605 | 4 |
| HS06 | Refrigeration plant | (-1.1 , -0.15 , 18.07) | 5.605 | 0.327 | 5.615 | 5 |
| HS04 | Solar collector | (-1.21 , 0.34 , 16.76) | 5.297 | 0.347 | 5.309 | 6 |
| HEAT RECOVERY SUBSYSTEM | | FUZZY RATING | DEFFUZIFICATION | | | RANKING |
| ID | Technology | $r_{RS}$ | $x_{RS}$ | $y_{RS}$ | $R_{RS}$ | |
| RSbc | No heat recovery | (-0.31 , 0.1 , 13.35) | 4.38 | 0.338 | 4.393 | 3 |
| RS02 | Exhaust air recirculation | (-1.77 , 0.3 , 40.66) | 13.062 | 0.338 | 13.067 | 1 |
| RS03 | Exhaust air heat exchanger | (-1.97 , -0.59 , 30.83) | 9.425 | 0.319 | 9.431 | 2 |
| RS01 | No heat recovery | (-0.31 , 0.1 , 13.35) | 4.38 | 0.338 | 4.393 | 3 |

## Annex 5-9. Ratings and rankings of the system technologies - selection of new facilities

| SYSTEM ALTERNATIVE | | SUBSYSTEM | | | FUZZY RATING | DEFFUZIFICATION | | | RANKING |
|---|---|---|---|---|---|---|---|---|---|
| ID | Technology | PS | HS | RS | $r_A$ | $x_A$ | $y_A$ | $R_A$ | |
| A257 | Pneumatic flash dryer - Boiler-renew | PS15 | HS02 | RS02 | (-0.58 , 0.73 , 68.2) | 22.78 | 0.34 | 22.78 | 1 |
| A258 | Pneumatic flash dryer - Boiler-renew | PS15 | HS02 | RS03 | (-0.59 , 0.68 , 65.71) | 21.94 | 0.34 | 21.94 | 2 |
| A185 | Direct rotary dryer - Boiler-renewabl | PS11 | HS02 | RS02 | (-0.66 , 0.55 , 63.9) | 21.27 | 0.34 | 21.27 | 3 |
| A254 | Pneumatic flash dryer - Boiler/heater | PS15 | HS01 | RS02 | (-0.58 , 0.6 , 62.62) | 20.88 | 0.34 | 20.88 | 4 |
| A203 | Fluidized bed dryer - Boiler-renewab | PS12 | HS02 | RS02 | (-0.66 , 0.51 , 62.78) | 20.88 | 0.34 | 20.88 | 5 |
| A260 | Pneumatic flash dryer - Boiler-mixed | PS15 | HS03 | RS02 | (-0.58 , 0.65 , 62.17) | 20.75 | 0.34 | 20.75 | 6 |
| A256 | Pneumatic flash dryer - Boiler-renew | PS15 | HS02 | RS01 | (-0.52 , 0.69 , 61.3) | 20.49 | 0.34 | 20.49 | 7 |
| A186 | Direct rotary dryer - Boiler-renewabl | PS11 | HS02 | RS03 | (-0.67 , 0.51 , 61.42) | 20.42 | 0.34 | 20.42 | 8 |
| A076 | Rotary steam tube dryer - Boiler-ren | PS05 | HS02 | RS01 | (-0.48 , 0.66 , 60.47) | 20.22 | 0.34 | 20.22 | 9 |
| A255 | Pneumatic flash dryer - Boiler/heater | PS15 | HS01 | RS03 | (-0.59 , 0.56 , 60.14) | 20.04 | 0.34 | 20.04 | 10 |
| A204 | Fluidized bed dryer - Boiler-renewab | PS12 | HS02 | RS03 | (-0.67 , 0.47 , 60.3) | 20.03 | 0.34 | 20.04 | 11 |
| A261 | Pneumatic flash dryer - Boiler-mixed | PS15 | HS03 | RS03 | (-0.59 , 0.61 , 59.69) | 19.9 | 0.34 | 19.9 | 12 |
| A182 | Direct rotary dryer - Boiler/heater-no | PS11 | HS01 | RS02 | (-0.66 , 0.43 , 58.33) | 19.36 | 0.34 | 19.37 | 13 |
| A188 | Direct rotary dryer - Boiler-mixed typ | PS11 | HS03 | RS02 | (-0.66 , 0.48 , 57.87) | 19.23 | 0.34 | 19.23 | 14 |
| A200 | Fluidized bed dryer - Boiler/heater-n | PS12 | HS01 | RS02 | (-0.66 , 0.38 , 57.21) | 18.98 | 0.34 | 18.98 | 15 |
| A184 | Direct rotary dryer - Boiler-renewabl | PS11 | HS02 | RS01 | (-0.59 , 0.52 , 57) | 18.98 | 0.34 | 18.98 | 16 |
| A206 | Fluidized bed dryer - Boiler-mixed ty | PS12 | HS03 | RS02 | (-0.66 , 0.43 , 56.76) | 18.84 | 0.34 | 18.84 | 17 |
| A253 | Pneumatic flash dryer - Boiler/heater | PS15 | HS01 | RS01 | (-0.52 , 0.56 , 55.73) | 18.59 | 0.34 | 18.59 | 18 |
| A202 | Fluidized bed dryer - Boiler-renewab | PS12 | HS02 | RS01 | (-0.6 , 0.47 , 55.89) | 18.59 | 0.34 | 18.59 | 19 |
| A183 | Direct rotary dryer - Boiler/heater-no | PS11 | HS01 | RS03 | (-0.67 , 0.38 , 55.84) | 18.52 | 0.34 | 18.52 | 20 |
| A259 | Pneumatic flash dryer - Boiler-mixed | PS15 | HS03 | RS01 | (-0.52 , 0.61 , 55.27) | 18.46 | 0.34 | 18.46 | 21 |
| A189 | Direct rotary dryer - Boiler-mixed typ | PS11 | HS03 | RS03 | (-0.67 , 0.43 , 55.39) | 18.39 | 0.34 | 18.39 | 22 |
| A073 | Rotary steam tube dryer - Boiler/hea | PS05 | HS01 | RS01 | (-0.48 , 0.54 , 54.9) | 18.32 | 0.34 | 18.32 | 23 |
| A079 | Rotary steam tube dryer - Boiler-mix | PS05 | HS03 | RS01 | (-0.48 , 0.58 , 54.45) | 18.18 | 0.34 | 18.19 | 24 |
| A201 | Fluidized bed dryer - Boiler/heater-n | PS12 | HS01 | RS03 | (-0.67 , 0.34 , 54.73) | 18.13 | 0.34 | 18.13 | 25 |
| A207 | Fluidized bed dryer - Boiler-mixed ty | PS12 | HS03 | RS03 | (-0.67 , 0.39 , 54.27) | 18 | 0.34 | 18 | 26 |
| A113 | Direct cabinet dryer - Boiler-renewat | PS07 | HS02 | RS02 | (-0.51 , 0.67 , 53.81) | 17.99 | 0.34 | 17.99 | 27 |
| A040 | Plate dryer - Boiler-renewable energ | PS03 | HS02 | RS01 | (-0.34 , 0.66 , 53.06) | 17.79 | 0.34 | 17.79 | 28 |
| A114 | Direct cabinet dryer - Boiler-renewat | PS07 | HS02 | RS03 | (-0.52 , 0.63 , 51.33) | 17.14 | 0.34 | 17.15 | 29 |
| A181 | Direct rotary dryer - Boiler/heater-no | PS11 | HS01 | RS01 | (-0.6 , 0.39 , 51.43) | 17.07 | 0.34 | 17.08 | 30 |
| A193 | Direct rotary dryer - Heat pump - No | PS11 | HS05 | RS01 | (-0.52 , 0.49 , 51) | 16.99 | 0.34 | 16.99 | 31 |
| A187 | Direct rotary dryer - Boiler-mixed typ | PS11 | HS03 | RS01 | (-0.6 , 0.44 , 50.98) | 16.94 | 0.34 | 16.94 | 32 |
| A199 | Fluidized bed dryer - Boiler/heater-n | PS12 | HS01 | RS01 | (-0.6 , 0.35 , 50.31) | 16.69 | 0.34 | 16.69 | 33 |
| A211 | Fluidized bed dryer - Heat pump - N | PS12 | HS05 | RS01 | (-0.52 , 0.45 , 49.88) | 16.6 | 0.34 | 16.61 | 34 |
| A205 | Fluidized bed dryer - Boiler-mixed ty | PS12 | HS03 | RS01 | (-0.6 , 0.39 , 49.86) | 16.55 | 0.34 | 16.56 | 35 |
| A131 | Direct tunnel dryer - Boiler-renewabl | PS08 | HS02 | RS02 | (-0.52 , 0.5 , 49.6) | 16.53 | 0.34 | 16.53 | 36 |
| A110 | Direct cabinet dryer - Boiler/heater-r | PS07 | HS01 | RS02 | (-0.52 , 0.54 , 48.24) | 16.09 | 0.34 | 16.09 | 37 |
| A116 | Direct cabinet dryer - Boiler-mixed ty | PS07 | HS03 | RS02 | (-0.52 , 0.59 , 47.78) | 15.95 | 0.34 | 15.96 | 38 |
| A037 | Plate dryer - Boiler/heater-non renew | PS03 | HS01 | RS01 | (-0.34 , 0.53 , 47.48) | 15.89 | 0.34 | 15.89 | 39 |
| A043 | Plate dryer - Boiler-mixed type - No h | PS03 | HS03 | RS01 | (-0.34 , 0.58 , 47.03) | 15.76 | 0.34 | 15.76 | 40 |
| A004 | Contact cabinet dryer - Boiler-renew | PS01 | HS02 | RS01 | (-0.29 , 0.65 , 46.84) | 15.73 | 0.34 | 15.74 | 41 |
| A112 | Direct cabinet dryer - Boiler-renewat | PS07 | HS02 | RS01 | (-0.45 , 0.63 , 46.91) | 15.7 | 0.34 | 15.7 | 42 |
| A132 | Direct tunnel dryer - Boiler-renewabl | PS08 | HS02 | RS03 | (-0.52 , 0.46 , 47.12) | 15.68 | 0.34 | 15.69 | 43 |
| A111 | Direct cabinet dryer - Boiler/heater-r | PS07 | HS01 | RS03 | (-0.53 , 0.5 , 45.75) | 15.24 | 0.34 | 15.25 | 44 |
| A117 | Direct cabinet dryer - Boiler-mixed ty | PS07 | HS03 | RS03 | (-0.52 , 0.55 , 45.3) | 15.11 | 0.34 | 15.11 | 45 |
| A128 | Direct tunnel dryer - Boiler/heater-no | PS08 | HS01 | RS02 | (-0.52 , 0.38 , 44.03) | 14.63 | 0.34 | 14.63 | 46 |
| A022 | Contact tunnel dryer - Boiler-renewat | PS02 | HS02 | RS01 | (-0.3 , 0.53 , 43.29) | 14.51 | 0.34 | 14.51 | 47 |
| A134 | Direct tunnel dryer - Boiler-mixed typ | PS08 | HS03 | RS02 | (-0.52 , 0.43 , 43.57) | 14.49 | 0.34 | 14.5 | 48 |
| A130 | Direct tunnel dryer - Boiler-renewabl | PS08 | HS02 | RS01 | (-0.45 , 0.47 , 42.7) | 14.24 | 0.34 | 14.24 | 49 |
| A001 | Contact cabinet dryer - Boiler/heater | PS01 | HS01 | RS01 | (-0.3 , 0.52 , 41.27) | 13.83 | 0.34 | 13.84 | 50 |
| A109 | Direct cabinet dryer - Boiler/heater-r | PS07 | HS01 | RS01 | (-0.45 , 0.51 , 41.34) | 13.8 | 0.34 | 13.8 | 51 |
| A129 | Direct tunnel dryer - Boiler/heater-no | PS08 | HS01 | RS03 | (-0.53 , 0.33 , 41.54) | 13.78 | 0.34 | 13.79 | 52 |
| A121 | Direct cabinet dryer - Heat pump - N | PS07 | HS05 | RS01 | (-0.37 , 0.61 , 40.91) | 13.72 | 0.34 | 13.72 | 53 |
| A007 | Contact cabinet dryer - Boiler-mixed | PS01 | HS03 | RS01 | (-0.3 , 0.57 , 40.82) | 13.7 | 0.34 | 13.7 | 54 |
| A115 | Direct cabinet dryer - Boiler-mixed ty | PS07 | HS03 | RS01 | (-0.45 , 0.56 , 40.89) | 13.66 | 0.34 | 13.67 | 55 |
| A135 | Direct tunnel dryer - Boiler-mixed typ | PS08 | HS03 | RS03 | (-0.53 , 0.38 , 41.09) | 13.65 | 0.34 | 13.65 | 56 |
| A118 | Direct cabinet dryer - Solar collector | PS07 | HS04 | RS01 | (-0.43 , 0.5 , 38.23) | 12.77 | 0.34 | 12.77 | 57 |
| A019 | Contact tunnel dryer - Boiler/heater-r | PS02 | HS01 | RS01 | (-0.3 , 0.41 , 37.71) | 12.61 | 0.34 | 12.61 | 58 |
| A025 | Contact tunnel dryer - Boiler-mixed ty | PS02 | HS03 | RS01 | (-0.3 , 0.46 , 37.26) | 12.47 | 0.34 | 12.48 | 59 |
| A127 | Direct tunnel dryer - Boiler/heater-no | PS08 | HS01 | RS01 | (-0.45 , 0.34 , 37.13) | 12.34 | 0.34 | 12.34 | 60 |
| A139 | Direct tunnel dryer - Heat pump - No | PS08 | HS05 | RS01 | (-0.38 , 0.44 , 36.7) | 12.25 | 0.34 | 12.26 | 61 |
| A133 | Direct tunnel dryer - Boiler-mixed typ | PS08 | HS03 | RS01 | (-0.45 , 0.39 , 36.67) | 12.2 | 0.34 | 12.21 | 62 |
| A286 | Freeze dryer - Refrigeration plant - N | PS16 | HS06 | RS01 | (-0.51 , -0.18 , 34.89) | 11.4 | 0.33 | 11.4 | 63 |
| A136 | Direct tunnel dryer - Solar collector - | PS08 | HS04 | RS01 | (-0.43 , 0.33 , 34.02) | 11.31 | 0.34 | 11.31 | 64 |

Annex 5-10. Ratings and rankings of the system technologies - technology change of the existing facilities

| SYSTEM ALTERNATIVE | | SUBSYSTEM | | | FUZZY RATING | DEFFUZIFICATION | | | RANKING |
|---|---|---|---|---|---|---|---|---|---|
| ID | Technology | PS | HS | RS | $r_A$ | $x_A$ | $y_A$ | $R_A$ | |
| Abc | Pneumatic flash dryer - Boiler-renew | PSbc | HSbc | RSbc | (-0.67 , 0.22 , 53.7) | 17.75 | 0.34 | 17.75 | 51 |
| A257 | Pneumatic flash dryer - Boiler-renew | PS15 | HS02 | RS02 | (-0.64 , 0.93 , 77.27) | 25.85 | 0.34 | 25.85 | 1 |
| A258 | Pneumatic flash dryer - Boiler-renew | PS15 | HS02 | RS03 | (-0.66 , 0.84 , 74.6) | 24.93 | 0.34 | 24.93 | 2 |
| A185 | Direct rotary dryer - Boiler-renewabl | PS11 | HS02 | RS02 | (-0.73 , 0.74 , 74.54) | 24.85 | 0.34 | 24.85 | 3 |
| A254 | Pneumatic flash dryer - Boiler/heater | PS15 | HS01 | RS02 | (-0.65 , 0.85 , 74.23) | 24.81 | 0.34 | 24.81 | 4 |
| A076 | Rotary steam tube dryer - Boiler-rene | PS05 | HS02 | RS01 | (-0.56 , 0.98 , 73.68) | 24.7 | 0.34 | 24.7 | 5 |
| A203 | Fluidized bed dryer - Boiler-renewab | PS12 | HS02 | RS02 | (-0.73 , 0.71 , 73.96) | 24.65 | 0.34 | 24.65 | 6 |
| A260 | Pneumatic flash dryer - Boiler-mixed | PS15 | HS03 | RS02 | (-0.65 , 0.88 , 72.67) | 24.3 | 0.34 | 24.3 | 7 |
| A186 | Direct rotary dryer - Boiler-renewabl | PS11 | HS02 | RS03 | (-0.74 , 0.65 , 71.87) | 23.93 | 0.34 | 23.93 | 8 |
| A255 | Pneumatic flash dryer - Boiler/heater | PS15 | HS01 | RS03 | (-0.66 , 0.76 , 71.56) | 23.89 | 0.34 | 23.89 | 9 |
| A182 | Direct rotary dryer - Boiler/heater-no | PS11 | HS01 | RS02 | (-0.73 , 0.66 , 71.5) | 23.81 | 0.34 | 23.81 | 10 |
| A204 | Fluidized bed dryer - Boiler-renewab | PS12 | HS02 | RS03 | (-0.74 , 0.62 , 71.3) | 23.72 | 0.34 | 23.73 | 11 |
| A073 | Rotary steam tube dryer - Boiler/heat | PS05 | HS01 | RS01 | (-0.56 , 0.9 , 70.64) | 23.66 | 0.34 | 23.66 | 12 |
| A200 | Fluidized bed dryer - Boiler/heater-n | PS12 | HS01 | RS02 | (-0.73 , 0.63 , 70.93) | 23.61 | 0.34 | 23.61 | 13 |
| A256 | Pneumatic flash dryer - Boiler-renew | PS15 | HS02 | RS01 | (-0.54 , 0.91 , 69.86) | 23.41 | 0.34 | 23.41 | 14 |
| A261 | Pneumatic flash dryer - Boiler-mixed | PS15 | HS03 | RS03 | (-0.66 , 0.79 , 70) | 23.38 | 0.34 | 23.38 | 15 |
| A188 | Direct rotary dryer - Boiler-mixed typ | PS11 | HS03 | RS02 | (-0.73 , 0.69 , 69.94) | 23.3 | 0.34 | 23.3 | 16 |
| A079 | Rotary steam tube dryer - Boiler-mix | PS05 | HS03 | RS01 | (-0.56 , 0.93 , 69.08) | 23.15 | 0.34 | 23.15 | 17 |
| A206 | Fluidized bed dryer - Boiler-mixed ty | PS12 | HS03 | RS02 | (-0.73 , 0.66 , 69.36) | 23.1 | 0.34 | 23.1 | 18 |
| A183 | Direct rotary dryer - Boiler/heater-no | PS11 | HS01 | RS03 | (-0.74 , 0.57 , 68.84) | 22.89 | 0.34 | 22.89 | 19 |
| A201 | Fluidized bed dryer - Boiler/heater-n | PS12 | HS01 | RS03 | (-0.75 , 0.54 , 68.26) | 22.69 | 0.34 | 22.69 | 20 |
| A184 | Direct rotary dryer - Boiler-renewabl | PS11 | HS02 | RS01 | (-0.63 , 0.72 , 67.13) | 22.41 | 0.34 | 22.41 | 21 |
| A189 | Direct rotary dryer - Boiler-mixed typ | PS11 | HS03 | RS03 | (-0.74 , 0.6 , 67.28) | 22.38 | 0.34 | 22.38 | 22 |
| A253 | Pneumatic flash dryer - Boiler/heater | PS15 | HS01 | RS01 | (-0.55 , 0.83 , 66.82) | 22.37 | 0.34 | 22.37 | 23 |
| A202 | Fluidized bed dryer - Boiler-renewab | PS12 | HS02 | RS01 | (-0.63 , 0.69 , 66.55) | 22.21 | 0.34 | 22.21 | 24 |
| A207 | Fluidized bed dryer - Boiler-mixed ty | PS12 | HS03 | RS03 | (-0.74 , 0.57 , 66.7) | 22.18 | 0.34 | 22.18 | 25 |
| A193 | Direct rotary dryer - Heat pump - No | PS11 | HS05 | RS01 | (-0.54 , 0.77 , 66.17) | 22.13 | 0.34 | 22.13 | 26 |
| A113 | Direct cabinet dryer - Boiler-renewat | PS07 | HS02 | RS02 | (-0.48 , 0.95 , 65.34) | 21.94 | 0.34 | 21.94 | 27 |
| A211 | Fluidized bed dryer - Heat pump - No | PS12 | HS05 | RS01 | (-0.54 , 0.74 , 65.59) | 21.93 | 0.34 | 21.93 | 28 |
| A259 | Pneumatic flash dryer - Boiler-mixed | PS15 | HS03 | RS01 | (-0.55 , 0.86 , 65.26) | 21.86 | 0.34 | 21.86 | 29 |
| A181 | Direct rotary dryer - Boiler/heater-no | PS11 | HS01 | RS01 | (-0.63 , 0.64 , 64.09) | 21.37 | 0.34 | 21.37 | 30 |
| A199 | Fluidized bed dryer - Boiler/heater-n | PS12 | HS01 | RS01 | (-0.63 , 0.61 , 63.52) | 21.17 | 0.34 | 21.17 | 31 |
| A040 | Plate dryer - Boiler-renewable energ | PS03 | HS02 | RS01 | (-0.38 , 0.92 , 62.76) | 21.1 | 0.34 | 21.1 | 32 |
| A114 | Direct cabinet dryer - Boiler-renewat | PS07 | HS02 | RS03 | (-0.5 , 0.86 , 62.67) | 21.01 | 0.34 | 21.02 | 33 |
| A110 | Direct cabinet dryer - Boiler/heater-r | PS07 | HS01 | RS02 | (-0.49 , 0.88 , 62.3) | 20.9 | 0.34 | 20.9 | 34 |
| A187 | Direct rotary dryer - Boiler-mixed typ | PS11 | HS03 | RS01 | (-0.63 , 0.67 , 62.53) | 20.86 | 0.34 | 20.86 | 35 |
| A205 | Fluidized bed dryer - Boiler-mixed ty | PS12 | HS03 | RS01 | (-0.63 , 0.64 , 61.95) | 20.66 | 0.34 | 20.66 | 36 |
| A116 | Direct cabinet dryer - Boiler-mixed ty | PS07 | HS03 | RS02 | (-0.49 , 0.9 , 60.74) | 20.39 | 0.34 | 20.39 | 37 |
| A037 | Plate dryer - Boiler/heater-non renew | PS03 | HS01 | RS01 | (-0.38 , 0.84 , 59.72) | 20.06 | 0.34 | 20.06 | 38 |
| A111 | Direct cabinet dryer - Boiler/heater-r | PS07 | HS01 | RS03 | (-0.5 , 0.79 , 59.64) | 19.97 | 0.34 | 19.98 | 39 |
| A043 | Plate dryer - Boiler-mixed type - No h | PS03 | HS03 | RS01 | (-0.38 , 0.87 , 58.16) | 19.55 | 0.34 | 19.55 | 40 |
| A004 | Contact cabinet dryer - Boiler-renew | PS01 | HS02 | RS01 | (-0.31 , 0.93 , 57.89) | 19.51 | 0.34 | 19.51 | 41 |
| A112 | Direct cabinet dryer - Boiler-renewat | PS07 | HS02 | RS01 | (-0.38 , 0.93 , 57.93) | 19.49 | 0.34 | 19.5 | 42 |
| A117 | Direct cabinet dryer - Boiler-mixed ty | PS07 | HS03 | RS03 | (-0.5 , 0.81 , 58.08) | 19.46 | 0.34 | 19.47 | 43 |
| A121 | Direct cabinet dryer - Heat pump - N | PS07 | HS05 | RS01 | (-0.3 , 0.98 , 56.97) | 19.22 | 0.34 | 19.22 | 44 |
| A131 | Direct tunnel dryer - Boiler-renewabl | PS08 | HS02 | RS02 | (-0.49 , 0.65 , 55.99) | 18.72 | 0.34 | 18.72 | 45 |
| A001 | Contact cabinet dryer - Boiler/heater | PS01 | HS01 | RS01 | (-0.31 , 0.86 , 54.85) | 18.47 | 0.34 | 18.47 | 46 |
| A109 | Direct cabinet dryer - Boiler/heater-r | PS07 | HS01 | RS01 | (-0.39 , 0.86 , 54.89) | 18.45 | 0.34 | 18.46 | 47 |
| A007 | Contact cabinet dryer - Boiler-mixed | PS01 | HS03 | RS01 | (-0.31 , 0.88 , 53.29) | 17.96 | 0.34 | 17.96 | 48 |
| A115 | Direct cabinet dryer - Boiler-mixed ty | PS07 | HS03 | RS01 | (-0.39 , 0.88 , 53.33) | 17.94 | 0.34 | 17.95 | 49 |
| A132 | Direct tunnel dryer - Boiler-renewabl | PS08 | HS02 | RS03 | (-0.5 , 0.56 , 53.33) | 17.79 | 0.34 | 17.8 | 50 |
| A128 | Direct tunnel dryer - Boiler/heater-no | PS08 | HS01 | RS02 | (-0.49 , 0.57 , 52.95) | 17.68 | 0.34 | 17.68 | 52 |
| A022 | Contact tunnel dryer - Boiler-renewat | PS02 | HS02 | RS01 | (-0.31 , 0.73 , 51.27) | 17.23 | 0.34 | 17.24 | 53 |
| A134 | Direct tunnel dryer - Boiler-mixed typ | PS08 | HS03 | RS02 | (-0.49 , 0.6 , 51.39) | 17.17 | 0.34 | 17.17 | 54 |
| A129 | Direct tunnel dryer - Boiler/heater-no | PS08 | HS01 | RS03 | (-0.5 , 0.48 , 50.29) | 16.76 | 0.34 | 16.76 | 55 |
| A130 | Direct tunnel dryer - Boiler-renewabl | PS08 | HS02 | RS01 | (-0.39 , 0.63 , 48.58) | 16.27 | 0.34 | 16.28 | 56 |
| A135 | Direct tunnel dryer - Boiler-mixed typ | PS08 | HS03 | RS03 | (-0.5 , 0.51 , 48.73) | 16.24 | 0.34 | 16.25 | 57 |
| A019 | Contact tunnel dryer - Boiler/heater-r | PS02 | HS01 | RS01 | (-0.31 , 0.65 , 48.24) | 16.19 | 0.34 | 16.2 | 58 |
| A118 | Direct cabinet dryer - Solar collector | PS07 | HS04 | RS01 | (-0.39 , 0.77 , 48.04) | 16.14 | 0.34 | 16.15 | 59 |
| A139 | Direct tunnel dryer - Heat pump - No | PS08 | HS05 | RS01 | (-0.3 , 0.68 , 47.62) | 16 | 0.34 | 16 | 60 |
| A025 | Contact tunnel dryer - Boiler-mixed ty | PS02 | HS03 | RS01 | (-0.31 , 0.68 , 46.68) | 15.68 | 0.34 | 15.69 | 61 |
| A127 | Direct tunnel dryer - Boiler/heater-no | PS08 | HS01 | RS01 | (-0.39 , 0.55 , 45.54) | 15.24 | 0.34 | 15.24 | 62 |
| A133 | Direct tunnel dryer - Boiler-mixed typ | PS08 | HS03 | RS01 | (-0.39 , 0.58 , 43.98) | 14.73 | 0.34 | 14.73 | 63 |
| A136 | Direct tunnel dryer - Solar collector - | PS08 | HS04 | RS01 | (-0.39 , 0.47 , 38.69) | 12.92 | 0.34 | 12.93 | 64 |
| A286 | Freeze dryer - Refrigeration plant - N | PS16 | HS06 | RS01 | (-0.52 , -0.23 , 38.34) | 12.53 | 0.33 | 12.53 | 65 |

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Graz, 22. Jänner 2008

# BESCHEID

Aufgrund Ihres Ansuchens werden Sie gemäß § 60 des Universitätsgesetzes , BGBl.Nr.: 120/2002 in der geltenden Fassung, als ordentliche/r Studierende/r zum **DOKTORATSSTUDIUM DER TECHNISCHEN WISSENSCHAFTEN** zugelassen.

Sie werden gebeten, zur Aufnahme in der

**Allgemeinen Zulassungsfrist für das**
**SOMMER-SEMESTER 2008: 18. Februar bis 21. März 2007**
**Nachfrist bis 30. April 2008**
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| | Design of a decision support framework for the selection of thermal process technologies considering sustainability of the process, development of a decision support system for the selection of food drying technologies |
| Dates | Sep. 2004 – Dec. 2006 |
| | **Master of Engineering in Environmental Management, University of** |

**Technology, Vietnam National University – Ho Chi Minh city**

Focus on environment and natural resources management. The master thesis included assessment of the situation and the real treatment cost of the hazardous waste services and proposal of the solutions for the sustainable development of the hazardous waste service market in Ho Chi Minh city, Vietnam

Dates Sep. 1999 – Dec. 2003

**Bachelor of Engineering in Environmental Management, University of Technology, Vietnam National University – Ho Chi Minh city**

Focus on environment and natural resources management. The thesis was about the evaluation of the effectiveness and feasibility and the solutions for promulgating the government decree on environmental protection fee of waste water in Bien Hoa city - Dong Nai province, Vietnam

**Professional experience**

Dates Oct. 2004 – date

**Working at the Institute for Environment and Resources - Vietnam National University – Ho Chi Minh city**

Lecture and scientific research in the field of environmental management

Dates Mar. 2004 – Aug. 2004

**Working at the Centre of Environmental Technology - Technical Application and Production company, Ho Chi Minh city, Vietnam.**

Consultant in environmental impact assessment, environmental monitoring and HSE for industries

| | |
|---|---|
| **Languages** | |
| Vietnamese | Native speaker |
| English | Very good |

| | |
|---|---|
| **Computer skills** | Microsoft Office (Word, Excel, PowerPoint, Visio), AutoCAD, Photoshop |

| | |
|---|---|
| **Publications** | |
| Scientific journals | Do Thi Thu, H., Le Thanh, H., 2011. New methodology integrating environmental management accounting (EMA) and cleaner production assessment (CPA) to effectively control of industrial pollution. Journal of Science and Technology Development 14(3), 15–24. |
| | Le Thanh, H., Do Thi Thu, H., 2007. Evaluation of economic aspects of the industrial hazardous waste treatment activities in Ho Chi Minh city, Vietnam. Journal of Science and Technology Development 7(9). |
| Conferences | H. Do Thi Thu, H. Schnitzer, 2012. A decision support system considering sustainability for the selection of food drying technologies. Presented at the 2nd International Symposium on Processing and Drying of Foods Vegetables and Fruits, Selangor, Malaysia. |
| | Huyen Do Thi Thu, 2012. Development of a decision support system considering sustainability of food drying technologies. Presented at the 2nd Annual European Postgraduate Symposium on Sustainable Development (SDS 2012), Graz, Austria. |
| | H. Do Thi Thu, H. Le Thanh, H. Schnitzer, 2010. Expert approach to technology optimization toward energy efficiency of wort boiling process in brewing industry. Presented at the 13th Conference on Process Integration, |

Modeling and Optimisation for Energy Saving and Pollution Reduction (PRES 2010), Prague, Czech Republic.

L. Bac Tran, Huyen Do T. T., Hai Le T., 2006. Incorporating Environmental Cost Accounting into Cleaner Production Assessment at SMEs in Vietnam. Presented at the 9th Annual EMAN Conference - Environmental Management Accounting and Cleaner Production, Graz, Austria.

**Scholarships**

Dates Apr. 2008 – Sep. 2012

From the cooperation project between the Institute for Environment and Resources and the Swiss Federal Institute of Technology Lausanne (SDC project) support during the PhD study

Dates Sep. 1999 – Nov 2003

From the University of Technology, Vietnam national University – Ho Chi Minh city for high academic achievement